UNIVERSIDADE FEDERAL DE LAVRAS

MARIA CECÍLIA VIEIRA TOTTI

SOIL CARBON STOCKS, ECOSYSTEM SERVICES AND SOIL QUALITY IN THE PONTAL DO PARANAPANEMA REGION, BRAZIL

LAVRAS - MG
2025

MARIA CECÍLIA VIEIRA TOTTI

SOIL CARBON STOCKS, ECOSYSTEM SERVICES AND SOIL QUALITY IN THE PONTAL DO PARANAPANEMA REGION, BRAZIL

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para a obtenção do título de Doutora.

Orientador
Prof. DSc. Junior Cesar Avanzi

LAVRAS-MG
2025

Ficha de identificação da obra elaborada pelo(a) autor(a) através do Sistema de Geração Automática de Ficha Catalográfica da Biblioteca Universitária da UFLA.

Vieira Totti, Maria Cecília.
Soil carbon stocks, ecosystem services and soil quality in the Pontal do Paranapanema region, Brazil
/ Maria Cecilia Vieira Totti. 2025.
103 p. : il.

Orientador: Junior Cesar Avanzi

Tese (Doutorado) - Universidade Federal de Lavras, 2025. Bibliografia.

1. Sustentabilidade ambiental. 2. Sequestro de carbono. 3. Qualidade do solo. 4. Serviços ecossistêmicos. 5. Mudanças climáticas. I. Avanzi, Junior Cesar . II. Universidade Federal de Lavras. III. Título.

MARIA CECÍLIA VIEIRA TOTTI

ESTOQUES DE CARBONO NO SOLO, SERVIÇOS ECOSSISTÊMICOS E QUALIDADE DO SOLO NA REGIÃO DO PONTAL DO PARANAPANEMA, BRASIL

SOIL CARBON STOCKS, ECOSYSTEM SERVICES AND SOIL QUALITY IN THE PONTAL DO PARANAPANEMA REGION, BRAZIL

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para a obtenção do título de Doutora.

APROVADA em 25 de abril de 2025.

DSc. Ricardo de Oliveira Bordonal	CNPEM
Dr. Thaís Nascimento Pessoa	CNPEM
DSc. Yuri Lopes Zinn	UFLA
DSc. Marco Aurelio Carbone Carneiro	UFLA

Prof. DSc. Junior Cesar Avanzi
Orientador

LAVRAS-MG
2025

Ao Senhor Jesus Cristo, meu Deus, Nossa Senhora Aparecida, São José, São Miguel Arcanjo, Raziel e Anael

Dedico

AGRADECIMENTOS

Primeiramente à Deus pela saúde, força, entendimento e oportunidades dadas na minha vida, que me guiaram para concluir esse sonho.

À Nossa Senhora Aparecida, São José, São Miguel Arcanjo, Raziel e Anael, que me guiam, me protegem e me aproximam do Pai.

Aos meus pais Gilda Rodrigues Vieira e Pedro Baldin de Souza Totti, meus irmãos Pedro Henrique Vieira Totti e Alexandre Vieira Totti e meu namorado Vinicius Ferreira Fernandes. Obrigada por sempre estarem ao meu lado, sendo a minha base, me apoiando e inspirando.

Ao Departamento de Ciência do Solo da UFLA (DCS-UFLA). Aos professores, técnicos de laboratório e servidores pelo auxílio e demais contribuições para a realização deste trabalho, em especial aos professores Bruno Montoani, Sérgio Henrique Godinho, Yuri Lopes Zinn e Aline Oliveira.

Ao meu orientador Prof. Dr. Junior Cesar Avanzi pelo estímulo, paciência, ensinamentos transmitidos, confiança e exemplo de profissionalismo.

Ao Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq pelo apoio financeiro, possibilitando a realização dos meus estudos. O presente trabalho foi realizado com apoio do Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

À CTG Brasil e Instituto de Pesquisas Ecológicas, por ceder a área de estudo, e financiar parte dos custos gerados para a realização deste trabalho.

Aos meus colegas e amigos de departamento, Vanêssa, Priscilla, Ane, Amanda, Andrés, Téo, pela amizade, ajuda, apoio, risadas e lágrimas.

Aos alunos de Iniciação Científica e estagiários que tive o prazer de conviver e trabalhar lado a lado durante as atividades do estudo.

Ao Vinícius Ferreira Fernandes, que esteve tão presente em minha vida durante todo este processo, me trazendo muita positividade e motivação, fazendo com que tudo fosse um pouco mais leve.

E a todos aqueles que com sua contribuição fizeram possível a realização deste trabalho, agradeço de coração.

Muito obrigada!

🌱 *"O solo é a mãe de toda a vida; nele se encontram as raízes do passado e as sementes do futuro."*

(Ana Primavesi)

🙏 *"E tudo quanto fizerdes, fazei-o de todo o coração, como ao Senhor, e não aos homens."*

(Colossenses 3:23)

🏆 *"O sucesso é a soma de pequenos esforços repetidos dia após dia."*

(Robert Collier)

RESUMO

O manejo sustentável do solo é fundamental para garantir a produtividade agrícola, conservar os recursos naturais e manter os serviços ecossistêmicos essenciais ao equilíbrio ambiental frente aos desafios climáticos. O objetivo deste trabalho foi avaliar a sustentabilidade ambiental dos solos do Pontal do Paranapanema - SP sob diferentes usos, por meio de estoques de carbono, serviços ecossistêmicos e qualidade do solo, em uma área abrangendo quatro municípios da região. Primeiramente foram avaliados os estoques de carbono em Latossolos e Argissolos de textura grossa sob seis usos de terra contrastantes. Em seguida, foi proposto para região um índice de serviços ecossistêmicos (SE), que considerou os indicadores de sequestro de carbono (representa o armazenamento de C no solo), ciclagem de carbono (refere-se à dinâmica e transformação do C nos ecossistemas), fertilidade do solo (disponibilidade de nutrientes às plantas), estrutura do solo e regulação da água (capacidade de absorver, movimentar e armazenar água). Para finalizar, foi investigado como os indicadores microbiológicos influenciam a qualidade física e química destes solos. Os resultados mostraram que em ambos os tipos de solo, os menores estoques de carbono ocorreram sob o cultivo de mandioca. Em Argissolos, a restauração florestal e a cana-de-açúcar apresentaram os maiores estoques de carbono orgânico no solo (COS), enquanto em Latossolos, os maiores estoques ocorreram em florestas primárias e pastagens, sugerindo que culturas como gramíneas e perenes, com pouca perturbação do solo, são eficazes na preservação ou mesmo no sequestro de COS nessas áreas. O índice de serviços ecossistêmicos variou de 0,51 no uso do solo com cassava a 0,76 no uso com forest restoration, se apresentando como uma ferramenta estratégica para apoiar o manejo sustentável do solo em regiões tropicais, como o bioma Mata Atlântica, indicando que, quando bem manejados, os solos apresentaram uma maior capacidade de fornecimento de SE. Por fim, os indicadores microbiológicos, como o carbono da biomassa microbiana, a atividade da β-glicosidase, a respiração basal e quociente metabólico, mostraram-se sensíveis ao uso da terra, apresentando respostas claras às práticas de manejo. A integração destes indicadores nas avaliações da qualidade do solo permite uma compreensão mais profunda dos processos biológicos e da sua relevância para a sustentabilidade e funcionalidade dos solos tropicais. Este estudo também enfatiza a necessidade de práticas agrícolas sustentáveis para preservar a estrutura e a microbiota do solo, garantindo a resiliência e a funcionalidade dos solos tropicais. Ao alinhar-se com os Objetivos de Desenvolvimento Sustentável da ONU, a pesquisa contribui para ações de combate às mudanças climáticas (ODS 13), conservação de ecossistemas terrestres (ODS 15), uso responsável de recursos naturais (ODS 12), e promoção de práticas agrícolas sustentáveis (ODS 2). Essa abordagem interdisciplinar não apenas expande o conhecimento científico sobre os impactos do uso da terra nos serviços ecossistêmicos do solo, como também fornece suporte direto a produtores rurais e gestores ambientais na adoção de práticas mais responsáveis e efetivas, assegurando a resiliência dos solos tropicais frente às crescentes demandas ambientais e climáticas.

Palavras-chave: Latossolo; Argissolo; carbono do solo; solos tropicais**.**

ABSTRACT

Sustainable soil management is essential to ensure agricultural productivity, conserve natural resources, and maintain the ecosystem services that support environmental balance in the face of climate challenges. This study aimed to assess the ecological sustainability of soils in the Pontal do Paranapanema region (São Paulo, Brazil) under various land uses, focusing on carbon stocks, ecosystem services, and soil quality across four municipalities in the region. First, carbon stocks were evaluated in coarse-textured Oxisols and Ultisols under six contrasting land uses. Then, an ecosystem services (ES) index was proposed for the region, considering indicators of carbon sequestration (representing the storage of C in the soil), carbon cycling (referring to the dynamics and transformation of C in ecosystems), soil fertility (availability of nutrients to plants), soil structure, and water regulation (capacity to absorb, move, and store water). Finally, the influence of microbiological indicators on the physical and chemical quality of these soils was investigated. Results showed that in both soil types, the lowest carbon stocks occurred under cassava cultivation. In Ultisols, forest restoration and sugarcane exhibited the highest soil organic carbon (SOC) stocks, while in Oxisols, the highest stocks were observed under primary forests and pastures, suggesting that systems with perennial crops or grasses and minimal soil disturbance are effective in preserving or even enhancing SOC sequestration. The ecosystem services index ranged from 0.51 under cassava cultivation to 0.76 under forest restoration, highlighting its potential as a strategic tool to support sustainable soil management in tropical regions such as the Atlantic Forest biome. This indicates that, when properly managed, soils have a greater capacity to provide ES. Microbiological indicators—such as microbial biomass carbon, β-glucosidase activity, basal respiration, and the metabolic quotient—were sensitive to land use and showed clear responses to management practices. Integrating these indicators into soil quality assessments allows for a deeper understanding of biological processes and their relevance to the sustainability and functionality of tropical soils. This study also emphasizes the need for sustainable agricultural practices to preserve soil structure and microbial communities, ensuring soil resilience and functionality. Aligned with the United Nations Sustainable Development Goals (SDGs), this research contributes to climate change mitigation (SDG 13), terrestrial ecosystem conservation (SDG 15), responsible use of natural resources (SDG 12), and the promotion of sustainable agriculture (SDG 2). This interdisciplinary approach not only expands scientific knowledge on the impacts of land use on soil ecosystem services but also provides direct support to farmers and environmental managers in adopting more responsible and effective practices, ensuring the resilience of tropical soils in the face of increasing environmental and climate demands.

Keywords: Oxisols; Oltisols; soil carbon; climate change, tropical soils.

INDICADORES DE IMPACTO

A pesquisa desenvolvida na tese apresenta impactos significativos em diferentes áreas. Socialmente, promove a conscientização sobre a conservação ambiental e a adoção de práticas agrícolas sustentáveis, impactando diretamente agricultores e gestores ambientais no território do Pontal do Paranapanema, no bioma Mata Atlântica. O caráter extensionista da pesquisa é evidente, envolvendo a participação ativa de comunidades agrícolas locais e técnicos ambientais, que se beneficiam diretamente do índice de serviços ecossistêmicos criado, uma ferramenta prática para decisões de manejo sustentável. Estima-se que aproximadamente 20 profissionais, incluindo docentes, estudantes e técnicos da UFLA, estiveram diretamente envolvidos, ampliando a transferência de conhecimento para públicos externos à instituição. Economicamente, o trabalho contribui para a eficiência no uso de recursos naturais, reduzindo custos relacionados à degradação do solo e beneficiando pequenos e médios agricultores que dependem da qualidade do solo para sua subsistência. Além disso, a tecnologia desenvolvida oferece suporte para práticas agrícolas que priorizam a sustentabilidade e a produtividade. No aspecto tecnológico, a pesquisa destaca-se pela abordagem inovadora na criação de índices, integrando análises científicas e estatísticas aplicadas, o que possibilita avanços na tecnologia de produção e na conservação do solo tropical. Culturalmente, reforça a valorização dos ecossistemas brasileiros, particularmente da Mata Atlântica, promovendo uma narrativa que conecta as comunidades locais à importância do solo como recurso essencial. Ao divulgar os resultados e incentivar práticas de restauração e preservação, a pesquisa fomenta mudanças culturais em direção à sustentabilidade ambiental. O território abrangido inclui áreas de floresta fragmentada, restauração, pastagens, cultivos de cana-de-açúcar, mandioca e rotação de culturas na região do Pontal do Paranapanema, impactando populações agrícolas locais que dependem diretamente do solo. Os impactos podem ser classificados nas áreas temáticas de meio ambiente, por sua contribuição à conservação de solos e mitigação das mudanças climáticas; tecnologia e produção, ao desenvolver ferramentas inovadoras para o manejo sustentável; educação, pela disseminação de conhecimentos e conscientização ambiental; e cultura, ao promover a preservação do patrimônio natural. A pesquisa está em alinhamento direto com diversos Objetivos de Desenvolvimento Sustentável (ODS) da ONU, como o ODS 2, ao promover práticas agrícolas que asseguram segurança alimentar; o ODS 6, ao tratar da regulação hídrica dos solos; o ODS 12, ao fomentar consumo e produção responsáveis; o ODS 13, ao incentivar o sequestro de carbono como estratégia contra mudanças climáticas; e o ODS 15, ao contribuir para a conservação e restauração de ecossistemas terrestres. Esses esforços demonstram o impacto abrangente da tese, que transcende a academia e beneficia amplamente a sociedade.

IMPACT INDICATORS

The research developed in this thesis presents significant impacts in various areas. Socially, it promotes greater awareness regarding environmental conservation and the adoption of sustainable agricultural practices, directly impacting farmers and environmental managers in the territory of Pontal do Paranapanema, within the Atlantic Forest biome. The research's extensionist character is evident, involving active participation from local agricultural communities and environmental technicians who benefit directly from the ecosystem services index created, a practical tool for sustainable management decisions. It is estimated that approximately 20 professionals, including professors, students, and technicians from UFLA, were directly involved, thus expanding knowledge transfer to external audiences beyond the institution. Economically, the work contributes to resource efficiency by reducing costs related to soil degradation, benefiting small and medium-sized farmers who depend on soil quality for their livelihoods. Furthermore, the developed technology supports agricultural practices that prioritize sustainability and productivity. In the technological aspect, the research stands out for its innovative approach in creating indices, integrating applied scientific and statistical analyses, enabling advancements in production technology and tropical soil conservation. Culturally, it reinforces the value of Brazilian ecosystems, particularly the Atlantic Forest, promoting a narrative that connects local communities to the importance of soil as a vital resource. Through disseminating results and encouraging restoration and preservation practices, the research fosters cultural shifts toward environmental sustainability. The impacted territory includes fragmented forest areas, restoration sites, pastures, sugarcane plantations, cassava cultivation, and crop rotation systems in the Pontal do Paranapanema region, affecting local farming populations who rely directly on soil. The impacts can be classified within the thematic areas of the National Policy on Extension: Environment, for its contribution to soil conservation and climate change mitigation; Technology and Production, through the development of innovative tools for sustainable management; Education, by disseminating knowledge and environmental awareness; and Culture, by promoting the preservation of natural heritage. The research aligns directly with several United Nations Sustainable Development Goals (SDGs), including SDG 2, by promoting practices that ensure food security; SDG 6, addressing soil water regulation; SDG 12, fostering responsible consumption and production; SDG 13, encouraging carbon sequestration as a strategy against climate change; and SDG 15, contributing to the conservation and restoration of terrestrial ecosystems. These efforts demonstrate the comprehensive impact of the thesis, which transcends academia and broadly benefits society.

LIST OF FIGURES

LIST OF TABLES

SUMÁRIO

ORGANIZATION OF THE THESIS

This thesis is organized into four sections. The first part presents the introduction, the justification for the project, and the overall objective of the thesis. The remaining sections comprise three papers based on experimental data.

In Paper 1, we explored the importance of soil organic carbon (SOC) reservoirs, which can be easily affected by land use changes, particularly in humid tropical sandy soils where organic decomposition is rapid and SOC stabilization is weak.

In Paper 2, we evaluated the soil's capacity to provide ecosystem services, such as carbon storage, carbon cycling, soil fertility, soil structure, and water regulation, and how each land use impacts these services.

Finally, in Paper 3, we introduced a soil quality index and examined the influence of microbiological soil quality indicators, such as β-glucosidase, microbial biomass carbon, basal respiration, and the metabolic coefficient, on the physical and chemical quality of the soil.

FIRST PART

INTRODUCTION

The Pontal do Paranapanema region is the second poorest area in the State of São Paulo. It has experienced deforestation since the early 20th century due to agricultural production. Following the oil crisis in the 1970s, there was a need to boost national ethanol production, which led to an increase in sugarcane cultivation and heightened interest in the region's lands (Pimenta and Rocha, 2018). In 2013, CTG Brazil (China Three Gorges Corporation) entered Brazil to generate hydroelectric power. Today, it stands as the second-largest power generator in the country, backed by private capital. Additionally, the region has a history of land disputes attributed to land-grabbing practices dating back to the 19th century (Origuéla et al., 2012).

The intense land occupation can result in a series of environmental damages, such as soil compaction, low organic matter and soil fertility, an increase of greenhouse gas emissions, and reduction of water infiltration and movement in the soil, with consequences for the recharge of water bodies (Vasconcelos et al., 2014). On the other hand, the conversion for conservation fields can lead to soil organic carbon (SOC) sequestration and improvement in soil quality (Lal, 2004).

Thus, to maintain the soil quality and yield, it is necessary to reclaim degraded areas. Its benefits include erosion control, water conservation, nutrient cycling, stable and sustainable crops, and soil carbon sequestration (Lal, 2018). It is important to fit the correct soil management to the soil type, since soils with higher clay content, such as Oxisols, have a better capability of carbon sequestration. The contrary happens with coarser-textured soils, which have a greater loss of carbon in the soil profile (Zinn et al., 2005a).

To offset the areas flooded by the damming of Paraná and Paranapanema rivers, CTG Brazil company promoted a planting of over 11 million trees, totaling 6,715 hectares of restored areas, and set conserved 2,818 hectares of areas for regeneration and conservation efforts (Adeodato, 2018). The recovery of these areas can be assessed through soil quality by utilizing physical, chemical, and microbiological indicators in regions undergoing forest restoration (Vicente et al., 2012). These indicators are frequently used as measures of soil quality due to their easy determination and low cost (Lana et al., 2017). Additionally, the soil quality indicators can be integrated into these indices (Scarpare et al., 2019), which effectively highlight the weaknesses and strengths of management systems (Cherubin et al., 2016).

THEORETICAL FRAMEWORK

History of land use and occupation in the Pontal do Paranapanema region.

Pontal do Paranapanema, located in the far west of the state of São Paulo, is the second poorest region in the state. The region is demarcated by the Paraná and Paranapanema rivers. After most of its forests were cut down at the beginning of the 20^{th} century, the region was turned over to agricultural production of crops such as cotton and coffee and occupied by pastures from the 1950s onwards (Origuéla et al., 2012). In addition, this region has a history of territorial disputes due to a large number of properties illegally acquired through “land-grabbing” (Feliciano, 2018).

With the oil crisis in the 1970s, Brazil needed to invest in new energy matrices, due to the PROÁLCOOL (National Alcohol Program) project with the aim of replacing part of the fleet of gasoline-powered cars with cars powered by ethanol, produced from sugarcane (Pimenta and Rocha, 2018). So, there was an urgent need to expand the areas of cultivation for agrofuel production in Pontal do Paranapanema (Adeodato, 2018). In an attempt to curb deforestation in the region, the Governor of the State of São Paulo, Franco Montoro, created the “Integrated Plan for the Development of Pontal do Paranapanema”, and the creation of the “Morro do Diabo State Park”, through Decree No. 25.342, of July 4, 1986 (Silva, 2010). In June 1990, the MST (Landless Rural Workers’ Movement) carried out its first major occupation in Pontal do Paranapanema, beginning the process of territorialization and the struggle for land in the region (Fernandes and Ramalho, 2001).

Pontal do Paranapanema is the western region in São Paulo State, where it is located the last remaining of the Atlantic Rainforest biome (Carrasco et al., 2020). The region is within what Thomaz Junior (2010) names hydro-agricultural business, which limits to the west of São Paulo, east of Mato Grosso do Sul, north-west of Paraná, Triângulo Mineiro, and south-southwest of Goiás State.

Thus, Pontal do Paranapanema stands out for having a history of pasture occupation and land conflicts, as well as the expansion of sugarcane crop. Covered by sediments of the Bauru-Caiuá aquifer, the whole region can be considered as naturally vulnerable, since it is an aquifer with direct recharge (Romagnoli and Manzione, 2018). Due to its water production, the region is also exploited by large construction projects, such as hydroelectric dams – which flood large areas of farmlands – and road and rail corridors, which also cause mass displacement (Fernandes et al., 2010). Initiatives of environmental protection and optimization of land use and occupation have consequences for the conservation of soils and water resources in a water basin, quantitatively or qualitatively (Silva et al., 2017).

Land use in the Pontal do Paranapanema

Intense land occupation can provoke a series of environmental damages. These speed up the degradation of the watershed, leading to losses in soil quality and water resources (Silva et al., 2017). The initial process of environmental degradation of an area is deforestation. Among the consequences of deforestation is a decline in soil productivity and local climate change (Soares et al., 2019). In addition, it leads to carbon dioxide (CO_2) emission into the atmosphere. It happens mainly through burning, decomposition of vegetal residues, and soil respiration (Souza, 2022). A report by the World Resources Institute (2024) showed that global CO_2 emissions in 2022 were 182 times higher than in 1850, the year of the Industrial Revolution.

Land use changes with the replacement of native vegetation by agricultural use can induce soil degradation (Souza, 2022) and significantly harm the provision of multiple ecosystem services (Foley et al., 2005). Carrasco et al. (2020) mapped land uses in the Pontal do Paranapanema, concluding that the dominant land use is pasture, with 48.4% in 2017. Farming was the second largest use, with a 45.4% increase between 1987 and 2017. The authors also pointed out that vegetated areas were low in all the years assessed. In another survey, Rodrigues et al. (2019) pointed out that more than 84% of the permanent preservation area remains with a deficit of tree vegetation.

When poorly managed, pastures also harm the environment. Besides economic impacts, such as reduced productivity and pasture quality, they have lower animal stocking capacity (Zanello and Micheels, 2025). After pasture, the most common land use in the Pontal do Paranapanema region is agricultural cultivation, with sugarcane as the most expressive (Rodrigues et al., 2019). The conventional soil management system used in the sugarcane can cause an increase in bulk density and a decrease in soil porosity and water infiltration (Vasconcelos et al., 2014). On the other hand, the no-till system provides a greater amount of organic material into the soil and high biological activity, favoring plant growth (Bertol et al., 2016).

Rodrigues et al. (2019) also report significant annual crop areas. Successive monoculture and extensive agricultural practices, and inadequate crop rotations lead to the degradation of soils and other natural resources, affecting food security (Hussain et al., 2021). A small rate of change in land use was by Carrasco et al. (2020). Despite the increase in growth rates is 0.4% a year, for 30 years, the region presented a serious deficit of native vegetation.

Among the main environmental risks that agricultural business entails are soil compaction, reduced aggregate stability (Silva et al., 1990), soil loss (Armbrust et al., 1994), increase in soil temperature (Carrasco et al., 2020; Pan and Ziaul, 2017), and pH change, sum of bases, bases saturation (Cardoso et al., 1992). Soil microorganisms are also affected, altering the decomposition of organic matter, and nutrient availability and absorption (Lange et al., 2019). In addition, there is a 16 to 20% loss of global soil C stock (Hussain et al., 2021).

The economic and social problems of these indiscriminate land use changes are significant, with implications for food security (Gazzoni, 2014), agriculture, health, social welfare, migration (Madden et al., 2020), land distribution, wildlife conservation, carbon sequestration and emissions, among others (Souza, 2022). Therefore, in order to minimize the impacts associated with environmental degradation, the adoption of sustainable soil management practices is inevitable. These practices help to maintain natural resources, provide food security, and improve soil quality. In addition, achieving the COP 21 goal of ending illegal deforestation by 2030 and recovering 12 Mha of native vegetation (Roque, 2015).

Soil quality indicator

Soil is an essential element of natural capital and performs fundamental ecological functions to provide several ecosystem services (Simth et al., 2021). Besides being the basis for crop production, soils filter water, and regulate its flow; and host the soil biota, which are the decomposing agents of dead plant material. In this sense, soil quality is fundamental for supporting the functioning of the ecosystem as well as for supplying ES (Drobnik et al., 2018). The measurement of soil quality is based on the evaluation of the attributes involved in the processes involved in the development of agricultural crops (Lana et al., 2017).

Among the soil attributes, soil texture is one of the main indicators of soil quality and productivity (Wang et al., 2018). It is a soil characteristic related to the primary particles (sand, silt, and clay) and their feel to the touch (friction, silkiness, and stickiness) (Bertol et al., 2016). Texture influences adhesion and cohesion between particles, as well as soil management. Clay contents are a key indicator of soil aggregation stability, as it represents the suspended solid fraction transported over greater distances by surface runoff.

One soil attribute that is influenced by both its particle size fractions and by management is bulk density. It corresponds to the mass of dry soil in a volume of soil. It is variable and depends on the soil's constituent material, structure, aggregation, porosity, land use, and management (Bicalho, 2011). For each soil, there is a critical bulk density, when it decreases or prevents root growth, according to Kumar (2024). Bulk density can influence other soil properties, such as gas exchange in the pore system, water retention and infiltration, root penetration, and nutrient cycling (Rabot et al., 2018). Influenced by bulk density, low macroporosity can help identify soil structural degradation, which affects oxygen diffusion, water infiltration, and drainage, and thus root development (Vengavasi et al., 2024).

When soils susceptible to compaction, such as Oxisols, are used for productive systems, degradation processes such as compaction and erosion can happen (Scarpare et al., 2019). It is known that Oxisols are among the most predominant soils in areas of risk in the Pontal do Paranapanema. However, they also stand out due to its low organic matter content, stable granular structure, and good drainage, which easily favors the vertical movement of solutes (Romagnoli and Manzione, 2018). On the other hand, sandy clay loam and sandy clay soils, such as the predominant soils in the region -Oxisols and Ultisols, present less capacity for water and nutrient retention, in this way, the plant induces root development in depth to make up for the lack of these resources (Otto et al., 2009).

In this context, in order to analyze the viability of soil use and management, the estimation of quality indicators is a very useful tool, as it is capable of assessing the system's capacity to be self-sustaining and viable. In addition, the indicators must be effective in pointing out the weaknesses and strengths of management systems (Cherubin et al., 2016).

Soil organic carbon

The determination of soil organic carbon (SOC) is also recommended for monitoring the soil quality (Franzluebbers, 2002), SOC is the greatest carbon pool in the biosphere (Sparks, 2019). The reduction of soil organic matter, besides boosting CO_2 emissions into the atmosphere, leads to soil degradation and its chemical, physical, and biological attributes (Vezzani and Mielniczuk, 2009). In this sense, SOC can be considered a soil quality indicator (Wink et al., 2019).

SOC stock is regulated by various factors, such as climate, relief, vegetation, parent material, soil texture and type (Stevenson and Cole, 1999), altitude (Zinn et al., 2018), and the frequency and depth of soil cultivation (Zinn et al., 2005b). Studies have shown that the stabilization of C in the soil is influenced by soil mineralogy. The clay, silt, and sand fractions play an important role in stabilizing C (Saidy et al., 2013). In soils with high sand content, a lower rate of organo-mineral associations is expected. This reduces the physical protection of soil organic matter (SOM) (Tenelli et al., 2025), making soils more sensitive to agricultural practices (Totti et al., 2025).

For Brun and Conceição (2010), in soils with higher sand content on the surface, such as some Oxisols, soil management must be conducted meticulously, due to their low carbon contents, making the correct management of these soils necessary in order to increase C through this soil class. When there is a change in land use, if agricultural cultivation is carried out with minimal disturbance, in addition to preserving its physical characteristics, it is also possible to recover the soil carbon stocks (Oliveira et al., 2022). After 20 to 40 years of forest restoration, soil C content can be reestablished, increased, or even decreased, according to the management adopted in that area (Specht and West, 2003).

A higher content of this element can help preserve the soil structure, forming bigger and more stable aggregates, which aid the retention of available water to plants and create greater permeability, drainage, and soil aeration. Soil carbon offers substrate and energy for sustaining microbial activity, and maintains a pool of N, P, and other nutrients, which provides productivity for plants, and helps mitigate climate changes (Milne et al., 2015).

Soil quality indices

Indices are a good tool for understanding soil quality indicators (Lal, 1999). Soil attributes can lead to which use has more benefits for sustainability in the study areas (Lopes et al., 2009). In addition, studies that look to integrate the link between soil quality and ES with decision-making are still scarce, making it necessary for more strategies that can ensure the sustainable provision of soil-related ES (Silva-Olaya et al., 2022).

The assessment of quality indicators in indices has been shown as a more and more helpful tool in the evaluation of the system's capacity to self-sustain and make itself viable in the present and future (Cherubin et al., 2016). Therefore, it reveals the weaknesses and strengths of land use and management, being capable of corroborating the importance of biodiversity to maintain ecological services (Oliveira et al., 2007).

According to Kroll et al. (2012), the provision of soil ES tends to be more influenced by soil management practices and land use intensity than by the use itself. Thus, there are no universal indicators, since every system has its characteristics, needing a group of indicators for the system in question. In this regard, by formulating these ecosystem services and soil quality indices, it is possible to assess the capacity of the management system to self-sustain and make itself viable.

OBJECTIVES

The objectives of our research were to evaluate the environmental sustainability of soils in the Pontal do Paranapanema – SP, under different uses, through carbon stocks, ecosystem services, and soil quality indices.

HYPOTHESES

Under similar land uses, Oxisols are expected to exhibit greater potential for carbon stabilization and improved soil quality indicators than Ultisols, suggesting that intrinsic mineralogical and textural properties may modulate land use effects on soil functioning.

Land uses with continuous vegetative cover—such as native forest, reforestation, and sugarcane—are hypothesized to foster greater carbon sequestration and enhanced soil quality compared to uses with seasonal cover or intensive management (e.g., cassava, annual crops), due to sustained organic inputs and lower disturbance intensity.

SECOND PART – PAPERS

Article 1 - Written by the standards of the scientific journal Geoderma Regional - Published version	
Article title:	Organic carbon stocks across various land use systems in sandy Ultisols and Oxisols in Brazil
Autores:	Maria Cecília Vieira Totti Yuri Lopes Zinn Sérgio Henrique Godinho Silva Bruno Montoani Silva Fernanda Almeida Bócoli Vanêssa Lopes de Faria Andrés Olaya Montes Salvador Francisco Acuña-Guzman Alexandre Uezu Laury Cullen Junior Vinícius Ferreira Fernandes Junior Cesar Avanzi
Periódico:	Geoderma Regional
ISSN	2352-0094
DOI	https://doi.org/10.1016/j.geodrs.2025.e00924

PAPER 1 - ORGANIC CARBON STOCKS ACROSS VARIOUS LAND USE SYSTEMS IN SANDY ULTISOLS AND OXISOLS IN BRAZIL

Maria Cecília Vieira Totti[a,b], Yuri Lopes Zinn[a], Sérgio Henrique Godinho Silva[a], Bruno Montoani Silva[a], Fernanda Almeida Bócoli[a], Vanêssa Lopes de Faria[a], Andrés Olaya Montes[a,b], Salvador Francisco Acuña-Guzman[c], Alexandre Uezu[d], Laury Cullen Junior[d], Vinícius Ferreira Fernandes[e], Junior Cesar Avanzi[a],*

[a] Department of Soil Science, Federal University of Lavras, Lavras, Minas Gerais 37200-900, Brazil

[b] Amazonian Research Center CIMAZ-MACAGUAL, University of the Amazon, Florencia 180002, Colombia

[c] Department of Agricultural and Biosystems Engineering, University of Puerto Rico-Mayagüez Campus, Mayagüez, PR 00681, USA

[d] Institute for Ecological Research, Faculty for Environmental Conservation and Sustainability, Nazaré Paulista, São Paulo 12960-000, Brazil

[e] Department of Soil and Fertilizer Research, Agronomic Institute of Campinas, Campinas, São Paulo 13020-902, Brazil

Received 12 September 2024

Accepted 25 January 2025

* Corresponding author.

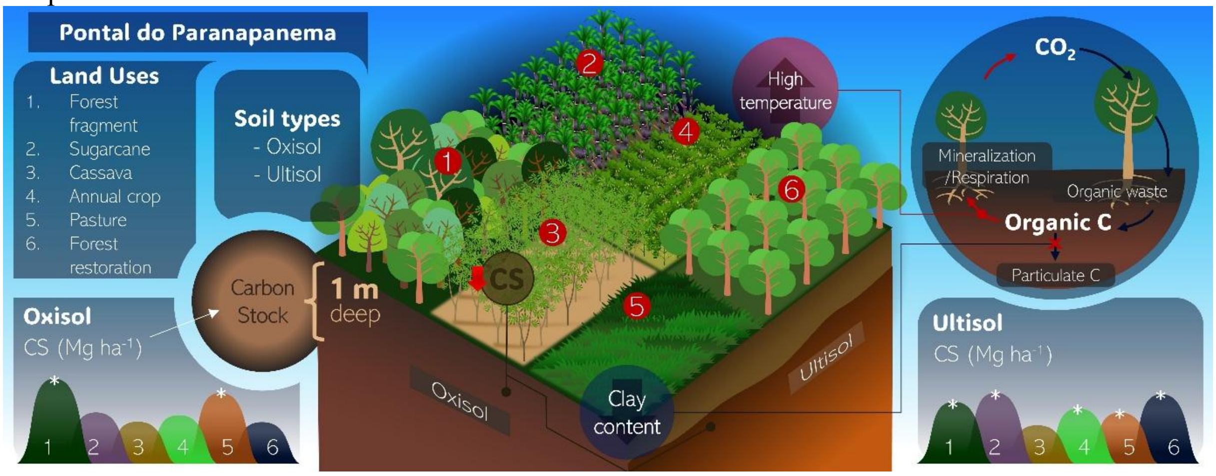
E-mail address: junior.avanzi@ufla.br (J.C. Avanzi).

Abstract

Soil organic carbon (SOC) is a major carbon pool that can be easily affected by land use change, especially in tropical humid sandy soils, where organic decomposition is fast and SOC stabilization is weak. Here, we assessed SOC stocks in coarse-textured Oxisols and Ultisols under six contrasting land uses in western São Paulo, Brazil, an area marked by warm temperatures, within the Atlantic Rainforest biome. Soils were sampled for bulk density and SOC content to a 1-m depth in areas under a) primary native forest, b) native forest restoration, c) pastures, d) sugarcane, e) cassava, and f) annual crops. Even under primary forests, SOC stocks were low relatively to other Brazilian soils under cooler climates and with finer textures, and the effect of land use changes varied with soil type. In both soil types, the lowest SOC stocks occurred under cassava cultivation, a traditional indigenous crop with low soil coverage and which requires intensive soil disturbance for harvesting. In Ultisols, forest restoration and sugarcane presented the highest SOC stocks, whereas in Oxisols, the highest stocks occurred under primary forests and pastures, suggesting that gramineous perennial crops with little soil disturbance are effective in preserving or even sequestering SOC in these areas. When only primary forests are compared, SOC stocks in Oxisols were higher than in Ultisols, probably due the effect of higher soil bulk densities on the Ultisols, rendering root development and thus SOC accrual in subsoil more difficult.

Keywords: Soil organic matter. Oxisols. Ultisols. Tropical Rainforest

Graphical abstract



1 Introduction

Soils are among the main terrestrial carbon (C) pools, storing approximately 2500 Billion metric tonnes of carbon, equivalent to 3.3 times the size of C of the atmosphere pool and 4.5 times the size of the biotic pool (Lal, 2004). Most of this C exists as soil organic carbon (SOC), the main component of soil organic matter, which in highly-weathered tropical soils, is critical to soil fertility and health (Bócoli et al., 2021). SOC directly and indirectly affects processes such as soil water retention, soil aggregation and resistance to erosion (Mantovani et al., 2024), and acts as the main energy and C source for the soil food web, and consequently promotes nutrient cycling (Haghverdi and Kooch, 2019). Globally, the conversion of forests to croplands has been reported to reduce not only biomass C but also SOC stocks (Babu et al., 2020; Koga et al., 2020; Padbhushan et al., 2022), the latter due to mechanical cultivation accelerating SOC decomposition and lower organic inputs (Zinn et al., 2002). Long-term annual soil cultivation significantly depletes SOC, consequently reducing nutrient supply through mineralization and decreasing nutrient retention by organic colloids, the primary source of cation exchange capacity (CEC) in tropical humid soils (Zinn et al., 2005).

Tropical rainforests play a fundamental role as terrestrial carbon sinks (Mantovani et al., 2024), and their year-round high net productivity can help mitigate anthropogenic

CO_2 emissions (Terra et al., 2023). According to Joly et al. (2014), the Atlantic Rainforest is Brazil's most threatened biome due to its long history of agricultural expansion, infrastructure and urban development, resulting in widespread deforestation. This biome historically occupied an area of ca. 1.1 Million km2, or 15 % of the national territory, but currently only 12.5 % of the original native forest area remains intact, or < 2 % of the total (Instituto Brasileiro de Florestas, 2024). However, Carvalho et al. (2010) suggested a substantial carbon storage capacity in deforested soils in the Atlantic Rainforest biome is still possible, by adoption of best management practices. For instance, forest restoration can store 178 % more SOC over time compared to monoculture systems, highlighting the potential advantage for carbon sequestration and storage (Lal, 2004; Yang et al., 2019). Among the various C pools in forest restoration areas, the largest pool is also SOC (Zanini et al., 2021). Conversely, conventional tillage for annual crops and even fast-growth forest plantations are known to deplete SOC in comparison to native vegetation in humid Brazil, especially in sandy soils, where stabilization of humic substances by sorption onto clays is limited (Zinn et al., 2002, Zinn et al., 2005). Thus, understanding how SOC in Atlantic Rainforest soils behave as C sinks or sources under various land use systems is essential for outlining mitigative measures and promoting sustainable agriculture.

Here, we aim to assess SOC stocks to a depth of 1 m in coarse-textured Ultisols and Oxisols in Southeastern Brazil, under six representative land use systems, with focus on forest restoration, a critical environmental recovery initiative whose potential for SOC sequestration potential is still poorly investigated. We hypothesized that: a) forest restoration would exhibit greater potential for carbon sequestration than agricultural land uses in sandy soils, and b) SOC stocks will be similarly influenced by the same land uses across both soil types.

2 Materials and methods

2.1 Study area

The area sampled is located within the Pontal do Paranapanema region, in the westernmost part of the State of São Paulo, Southeastern Brazil (Fig. 1), with local altitudes ranging between 350 and 560 m. The region has a tropical climate with a dry season, classified as Aw according to the Köppen system, with an average annual temperature of 21.9 °C and an annual precipitation of 1370 mm, with most rainfall occurring between December and February (summer), while the winter season is characterized by warm and dry conditions. The area is considered a part of the Atlantic Rainforest biome, which extends along Brazil's eastern coastline, and in some parts stretching hundreds of kilometers inland. Geologically, the area comprises aeolian sandstones from the Botucatu Formation, deposited above basaltic flows from the Serra Geral Formation (Silva et al., 2003). Deforestation in the area began in the 1950s (Uezu and Metzger, 2016), with no records of primary forest being cleared prior to this period. However, since then, part of the remnant forests have been partly degraded due to selective logging, fires and grazing, particularly at the forest edges.

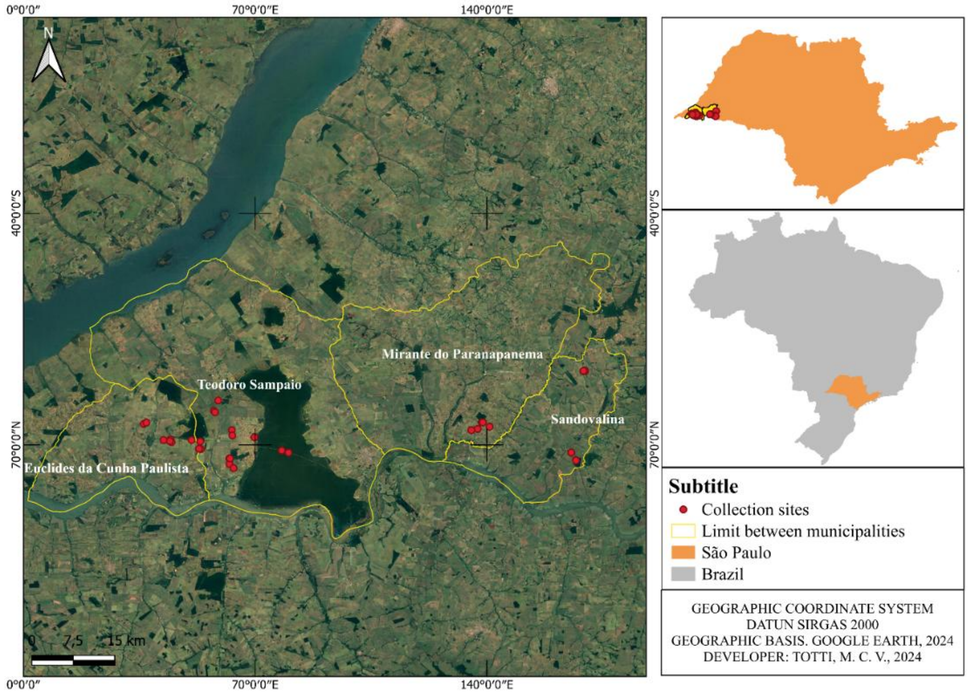


Fig. 1. Maps illustrating the study area highlighting the specific locations where soil samples were collected in the Pontal do Paranapanema region, São Paulo, Brazil.

To choose sites for correct sampling of Oxisols and Ultisols, we used the soil maps of the State of São Paulo elaborated by Rossi (2017). However, a brief soil description was performed at each site to verify whether the soil map unit accurately matched the field conditions. The sampling sites were chosen to include the two predominant soil types in the area and biome, namely Oxisols and Ultisols, and the most common land use systems in the State: 1) native forest fragments (Semideciduous Forest); 2) secondary forest restoration; 3) pastures featuring terraces as a conservation practice; 4) sugarcane, 5) cassava, and 6) annual crop rotations (soybean/corn) (Fig. 2). The secondary forest restorations are aged 15–20 years, and were established by planting seedlings of local native species, aiming the preservation of the original genetic pool (Mendes et al., 2021). The land use history of each site is detailed in Table S1 (Supplementary Data). The main features of each land use are robust soil cover under forest restoration areas (Fig. 3a), soil compaction but high straw cover in sugarcane plantation (Fig. 3b, d), deep root development in pasture (Fig. 3c), and excessive soil disturbance, poor soil cover and rill erosion under cassava (Fig. 3d).

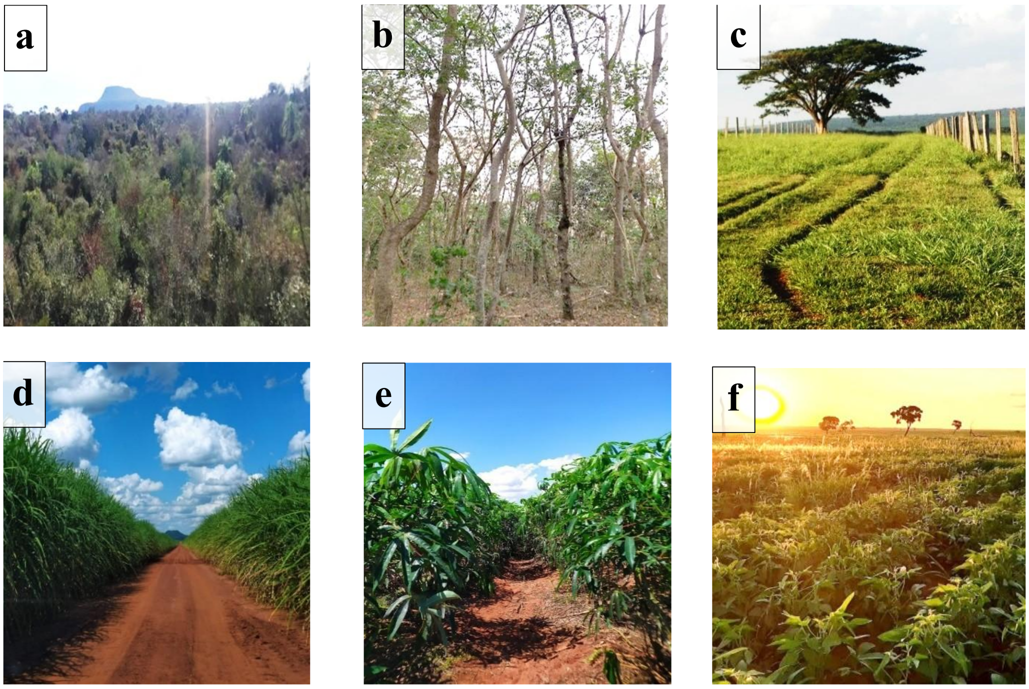


Fig. 2. Sampled land uses in study area: a) native forest fragment, b) secondary forest restoration, c) pasture, d) sugarcane, e) cassava, and f) annual crop rotation.

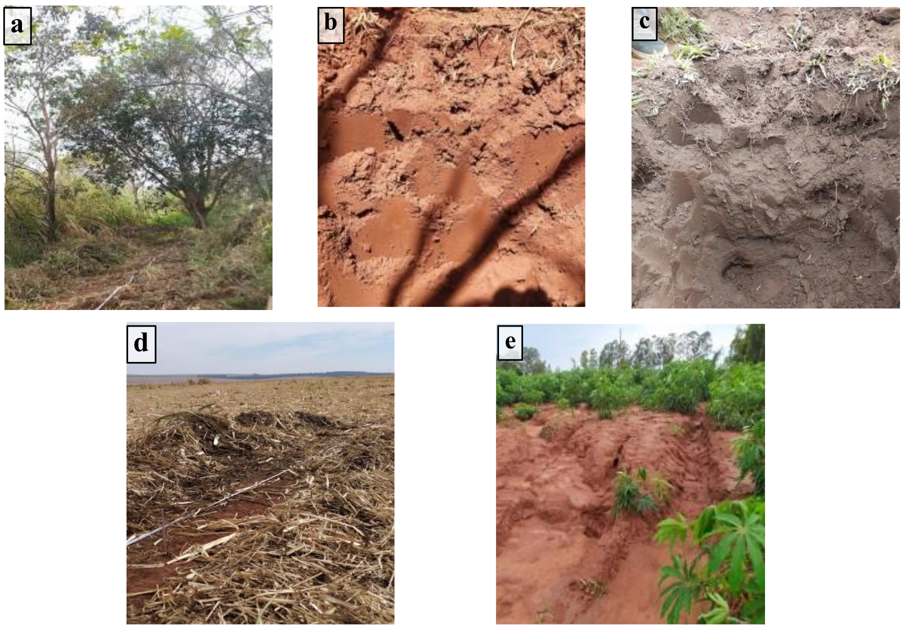


Fig. 3. Main features of land use systems: a) forest restoration area; b) soil compaction under sugarcane plantation; c) root development under pasture; d) sugarcane straw mulch after harvesting; and e) rill erosion under cassava cultivation due to excessive soil disturbance and poor soil cover.

The study area comprised 36 sampling locations derived from the combination of these two soil types and six land uses, with three replications.

2.2 Soil sampling and characterization

Soil sampling was conducted across two soil classes (Oxisols and Ultisols) and six land uses, with three replicates per combination, totaling 36 sampling points. At each point, five individual soil samples were collected and combined to form a composite sample. Samples for soil characterization were taken at depths of 0–20 cm and 80–100 cm using an auger. The sampling was performed in February 2023, during the rainy season. Soil particle-size distribution was determined using the pipette method after dispersion with 0.1 mol L^{-1} sodium hydroxide (NaOH), wet sieving, and siphoning according to Gee and Or (2002). Soil pH was determined in 0.01 mol L^{-1} $CaCl_2$; exchangeable Ca^{2+}, Mg^{2+} and Al^{3+} were extracted with 1 mol L^{-1} KCl; available K^+ and P were extracted with 0.05 mol L^{-1} HCl and 0.0125 mol L^{-1} H_2SO_4 (Mehlich-1) solution; and potential acidity (H + Al) was extracted in a 0.5 mol L^{-1} calcium acetate solution, pH 7.0. Exchangeable Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry and Al^{3+} by titration with NaOH; K^+ was determined in a flame photometer and P by colorimetry; H + Al was determined indirectly by reading in a potentiometer in SMP solution buffered at pH 7.0 (Quaggio and Van Raij, 2001). Soil organic matter was assessed using the wet combustion Walkley and Black (1934) method.

Undisturbed soil samples for SOC content and bulk density (Bd) analyses were taken using metal cores (5 cm height and diameter) at depths of 0–5, 5–10, 15–20, 45–50, and 95–100 cm (Blake and Hartge, 1986). SOC content were determined in samples of approximately 5 g of fine earth (<2 mm), further ground with mortar and pestle to a 100-mesh (0.149 mm) size, by dry combustion in an elemental analyzer (Flash EA1112, Thermo Electron Corporation, Milan, Italy) following Nelson and Sommers (1996) methodology.

The thickness of the evaluated soil layer was corrected to calculate mass-equivalent SOC stocks, considering changes in bulk density due to management, using the method suggested by Signor et al. (2014):

$$\text{Corrected depth} = \left(\frac{\text{Ref. Bd}}{\text{Corr. Bd}}\right) \times \text{dep. ref.} \quad (1)$$

where Ref. Bd. is the weighted average bulk density in the reference area under native forest (kg dm^{-3}), Corr. Bd is the weighted average bulk density in the assessed area (kg dm^{-3}), and dep. Ref. is the depth in the reference area for the layer equivalent to the one being corrected (cm). Mass-equivalent SOC stocks were calculated for each treatment and three standardized depths (0–20, 0–50, and 0–100 cm) as follows:

$$\text{Cstock} = \text{Bd} \times c \times L \times 100 \quad (2)$$

where Cstock is the carbon stocks (Mg ha^{-1}), Bd is the soil bulk density (Mg m^{-3}), c is the SOC content (%), L is the soil layer thickness (m), and 100 is a unit conversion factor. In addition, in order to better estimate SOC stocks in the subsoil standard layers, we averaged SOC and bulk density data between the two end sampling depths. For instance, to estimate SOC stocks at the 50–100 cm standard depth, we computed a mean value for SOC concentration and bulk density from data obtained for the 45–50 and 95–100 cm sampled depths.

2.3 Data analysis

To test the effects of land use on soil properties, the normality of the data for different soil indicators was verified using Shapiro-Wilk tests ($p > 0.05$), followed by analysis of variance (ANOVA). When ANOVA was significant ($p < 0.05$), means were compared using the Scott-Knott test ($p < 0.05$). Principal component analysis (PCA) was also performed to showcase the correlation between the measured variables and SOC stocks. All univariate and multivariate statistical analyses were conducted using RStudio 4.3.1 software.

3 Results

3.1 Soil characterization, bulk density and SOC concentrations

The sampled Oxisols and Ultisols, despite their different taxonomic classifications, showed similarities in key soil attributes (Table S2), consistent with highly weathered tropical humid soils. Clay contents were typically less than 20 % in the 0–20 cm layer, consistently with the sandstone parent material. Clay contents were generally higher at the 80–100 cm depth, and slightly more for Ultisols. Soil pH values were nearly neutral under forest fragments, with exchangeable Al^{3+} relatively low. Available K and P and CEC levels were generally low, even in cultivated fertilized soils. There were few significant differences between land use systems and soil types in regard to soil fertility indicators (Table S2).

Bulk density values (Fig. 4) were consistent with those reported for coarse-textured soils in Brazil, and considerably higher than commonly reported for clayey soils developed from sediments (Zinn et al., 2002). In both soil types but especially in Oxisols, primary forest fragments presented much lower bulk densities values than other land uses, throughout the 1-m soil profile. In Oxisols, bulk density was the lowest and varied little with depth, whereas in Ultisols, it increased considerably from the 0–5 cm to the 10–20 cm depth, with limited variation beneath that layer. In Ultisols, annual crops and cassava showed the highest bulk densities in the upper layers, reaching 1.66 g cm^{-3} at the 5–10 cm depth (Fig. 4a). The highest bulk density was reported under sugarcane in

Oxisols, where compaction resulted in values as high as 1.8 g cm⁻³ at the 15–20 cm depth (Fig. 4b).

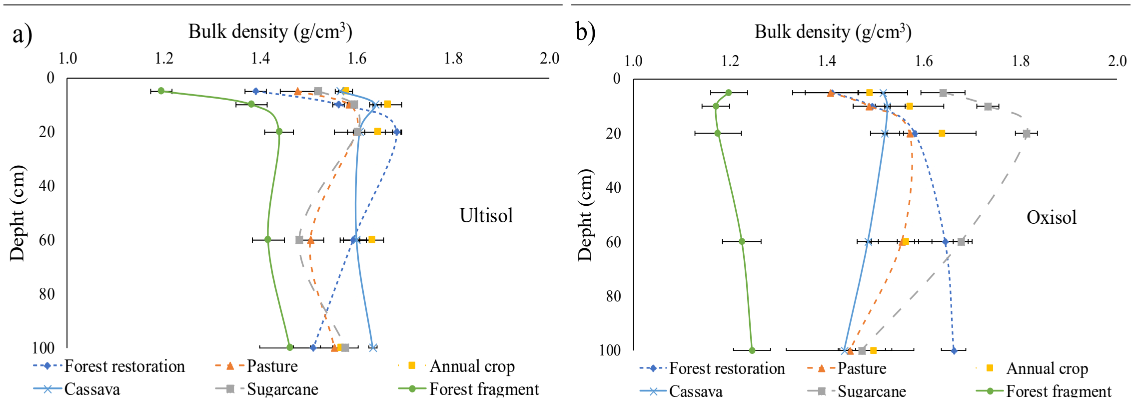


Fig. 4. Bulk densities of a) Ultisols and b) Oxisols, under different land uses along the top 1-m depth. The bars represent the standard error of the mean.

SOC concentrations were relatively low, always less than 1.2 % even under native forests, which however is consistent with values reported for coarse-textured tropical humid soils at low altitudes and under high mean annual temperatures (Zinn et al., 2002). In Ultisols, secondary forest restoration showed the highest values at the top 5 cm (1.09 %), with a significant decrease to 0.25 % at the 95–100 cm depth (Fig. 5). Although the native forest fragment did not show the highest SOC concentrations in the top 5 cm in Ultisols, it showed high values at the 95–100 cm depth (Fig. 5). Furthermore, SOC concentrations under primary forest were similar to those under sugarcane in the topsoil, pasture and annual crops in the 5–10 cm layer, and to all other land uses in the 10–20 cm, and 45–50 cm layers. Pasture and annual croplands showed similar patterns, with SOC contents of 0.63 % and 0.55 %, respectively, at the surface and 0.15 % and 0.23 % at the 1 m deepest layer. Cassava crops presented the lowest SOC content in most layers in Ultisols.

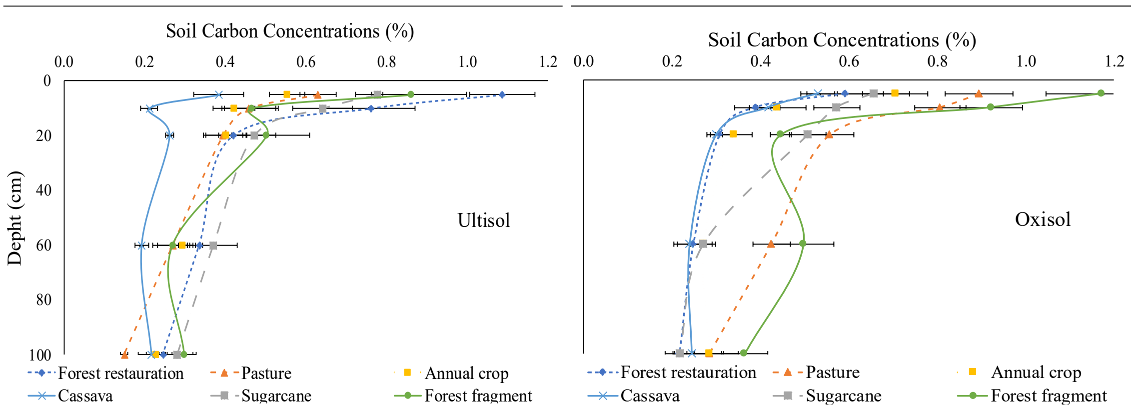


Fig. 5. Soil carbon content along the profile of Ultisols and Oxisols under different land uses. The bars represent the standard error of the mean.

In Oxisols, the primary forest fragment showed the highest SOC content, reaching 1.17 % at the surface layer, which was statistically different from all land uses except pasture, and reached 0.36 % at depth, not significantly different from other land uses. The secondary forest restoration in Oxisols presented low SOC concentrations, similar to cassava crops, reaching only ca. 0.6 % at the 0–5 cm depth.

3.2 SOC stocks

As with bulk density and SOC concentrations, the effect of land use systems on SOC stocks varied with soil type (Fig. 6). In Oxisols, SOC stocks under cassava and restoration forests at all three standard depths were nearly half of those under the primary forest fragments, which did not differ from the pasture in deeper layers. Conversely, in Ultisols, the highest SOC stocks were observed under secondary forest restoration, although not significantly different from the primary forest, and almost doubling SOC stocks under cassava, for the three depths. In Ultisols, sugarcane also presented high SOC stocks as compared to primary forests, which did not occur in Oxisols.

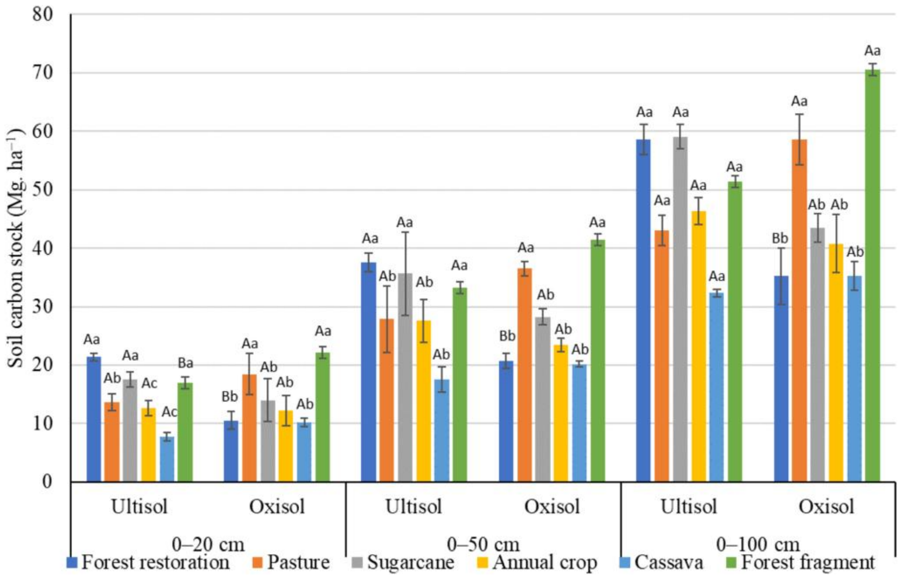


Fig. 6. Carbon stocks of Ultisols and Oxisols under different land uses at different depths. The bars represent the average standard error of the replicates. Within each depth, upper case letters indicate statistically significant differences among soil type for each land use, and lowercase letters indicate statistically significant differences due to land use within each soil type, inside at the 5 % significance level (Scott-Knott).

3.3 Principal component analysis

To better understand the drivers of soil carbon stock, several easily measurable chemical variables were analyzed through the principal component analysis (PCA) (Fig. 7). The PCA explained more than 60 % of the variance in the data between components 1 and 2. The plots indicate that SOC stocks were strongly correlated with carbon (C) and nitrogen (N) concentrations, as well as with clay and silt contents. SOC stocks were inversely correlated with bulk density, which in turn was inversely correlated with C content. Other soil fertility indicators, such as potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), and pH, were not significant in explaining SOC concentrations or stocks. As noted before, primary forest fragments and forest restoration presented the highest carbon stocks, particularly in Ultisols. Additionally, there was no grouping between the soils, indicating that both soils present the same patterns of SOC retention.

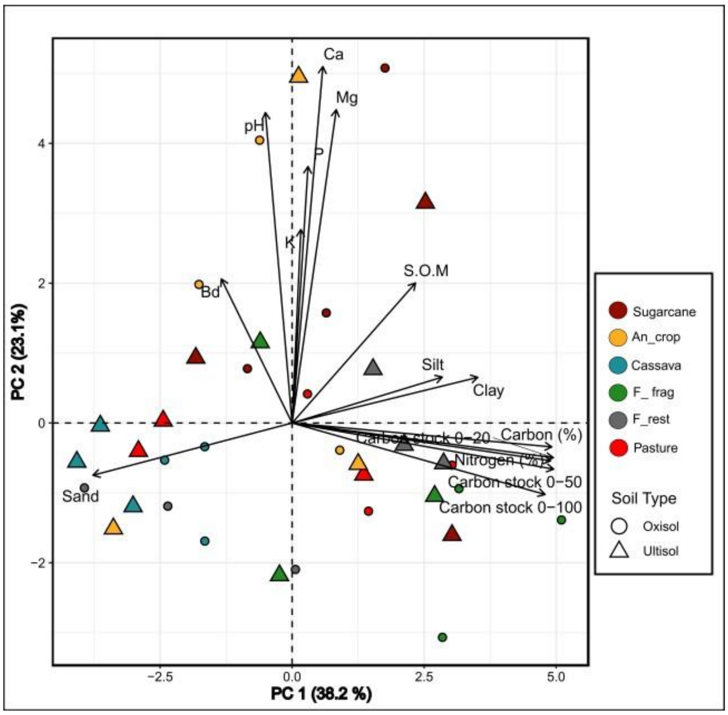


Fig. 7. Principal Component Analysis (PCA) of Ultisols and Oxisols under different land uses.

3.4 Discussion

Secondary forest restoration showed high SOC stock in Ultisols for all depth layers, which may have been driven by increased bulk densities below the 20-cm depth. This compaction is likely due to intensive agricultural land use prior to abandonment and subsequent planting of tree seedlings for forest restoration. The results suggest that the forest restoration in degraded Ultisols is very effective in regard to SOC accretion and stabilization, since it recovered after approximately only ca. 15 yrs., with obvious benefits also to other associated ecosystem services, such as nutrient cycling, soil fertility, water structuring and regulation, plant growth and food production.

This recovery was facilitated by the cessation of annual soil tillage and subsequent forest biomass accumulation (Fig. 3a) (Siqueira Neto et al., 2009). Therefore, forest restoration in areas with coarse-textured Ultisols proved to be a viable soil and environmental conservation strategy, serving as a C sink in both soils and biomass.

However, forest restoration performed differently in Oxisols, showing low SOC stocks. This might suggest that in Oxisols, characterized by their low fertility (Supplementary Material Table S2), may face challenges in enhancing recovery and SOC accrual –particularly through root system contributions, especially in deeper layers (James et al., 2019). Carbon input and renewal is much slower at deeper soil layers

(Moraes et al., 2002), and despite signs of improvement in Oxisol quality (e.g., reduced bulk density compared to agricultural land uses in surface, Fig. 4), the soil profile has not yet recovered former SOC levels (Freitas et al., 2018). These Oxisols thus still bear the impacts of past land use, which may also reflect that forest restoration efforts were performed without mechanical practices to ameliorate soil compaction, such as subsoiling. Diagnosing soil compaction and making informed decisions regarding its mitigation can then increase the success of environmental restoration strategies and associated benefits (Benevenute et al., 2020; Peixoto et al., 2019; Souza et al., 2021). The striking difference between bulk density patterns in Oxisols and Ultisols under native Brazilian forests has been shown earlier by Pádua et al. (2015). Another factor that may limit the increase in carbon stocks in forest restoration areas is the selection of plant species. The chosen plants were selected primarily for being native to the region and for their role in establishing forest corridors to support local fauna, rather than for their potential to contribute carbon to the soil.

Pastures presented intermediate bulk density values and SOC stocks, which can be considered a favorable outcome since this perennial land use requires minimal labor and inputs, while providing constant land coverage and C accrual. The sandy soil favors root development of grasses (Fig. 3c), contributing to C inputs through root turnover and decomposition (Santos et al., 2019). In fact, Rittl et al. (2017) observed SOC stocks under pastures similar to those under forests at a 30-cm depth, and a tendency for SOC increase over time.

In Oxisols, sugarcane plantations showed a pattern similar to those of forest restoration, with a comparable SOC stock. Similarly to the pastures, this may be due to the high number of fine, dense roots with relatively short lifespans that rapidly incorporate SOC, in addition to the presence of sugarcane straw (Fig. 3d). The discontinuation of burning before harvesting, as required by law in Brazil some years ago, has also increased the addition of straw into soils (Leal et al., 2013). Cherubin et al. (2018) reported an average rate of soil C increase in sugarcane fields without burning of 0.81 and 1.37 Mg ha^{-1} $year^{-1}$ for the 0–30 cm and 0–100 cm depths, respectively. Given that sugarcane in Brazil is largely used to produce ethanol biofuels, our data suggest that this crop is highly sustainable, in relation to the other agricultural uses evaluated, not only in offsetting fossil fuel emissions but also in sequestering C in soils.

Under annual crops, a significant portion of the total biomass is constantly removed from the production system (Anderson-Teixeira et al., 2009), leading to a decrease in SOC stocks. Forest soils exhibited approximately 20 % higher SOC stock at the 0–20 cm depth than a 40-year no-tillage system within the Atlantic Forest biome; however, when considering the entire soil profile (0–60 cm), the overall SOC stock was comparable between the soils under long-term no-tillage system and forest in an Ultisol (Thomaz and Kurasz, 2023). These findings suggest that adopting no-tillage management practices favors C accumulation under grain production.

Cassava crops had the lowest SOC values among all assessed land uses, which can be ascribed to a) low biomass production and soil coverage, b) intensive cultivation practices for planting, and c) heavy soil disturbance (Fig. 3e) through manual or mechanical harvesting, which promotes aggregate disruption, enhanced soil aeration, and thus accelerates SOC decomposition (Figueiredo et al., 2017). Thus, although cassava, like pastures and sugarcane, is also a perennial crop, which typically have a considerable potential for SOC sequestration (Ledo et al., 2020), its cultivation practices render it even more disruptive to soil structure and SOC than annual crops. Cassava was a major food staple for pre-Columbian peoples in Brazil, when it was planted in nomadic slash-and-burn agriculture, and still is a very traditional food source. However, it seems obvious that in its current conventional approach, on steady farms, cassava crops promote SOC depletion and soil degradation, turning the area into a net C source, especially where sand contents are high (Le et al., 2018). Innovative cassava cultivation methods are urgently needed to mitigate SOC depletion, whether through reduced soil disturbance or increased biomass yield, including cover crops.

In Ultisols, native forest fragments showed the third-highest SOC concentrations among land uses, and bulk densities in these areas were the lowest for Ultisols (Fig. 4). Although constant biomass accretion occurs, it was not sufficient to attain the highest SOC stocks, when compared to forest regeneration. Nevertheless, these values are comparable to those reported by Freitas et al. (2018) in nearby Guariba, São Paulo. In Oxisols, native forest fragment areas showed the highest SOC stocks, consistent with long-term protection and forest climax stages (Souza et al., 2021).

Higher SOC content and stocks in native forests under Oxisols compared to Ultisols are likely due to higher bulk densities in Ultisols, which hinder root development and C accrual, especially in subsurface layers. However, these values are relatively low compared to native forest soils with higher clay contents and at higher altitudes (i.e., due to lower mean temperatures) as reported by Zinn et al., 2002, Zinn et al., 2018. These results suggest that the Pontal do Paranapanema is not an area with high potential to store SOC, but at the same time, this study supports the conclusion that this and similar warm humid, sandy soil areas deserve more care when implementing some traditional food and annual crops, in order to minimize SOC losses.

When comparing the averages SOC stocks for land use and soil type combinations (Fig. 6), there were few significant differences between the land uses, especially for the 0–100 cm layer. This indicates strong variations in SOC stocks, especially true for sugarcane and pastures, which presented the wider error bars in Fig. 6, whereas cassava and annual crops presented the narrower variations, suggesting a consistent depletive effect on SOC. Jobbágy and Jackson (2000) highlighted that plant types significantly affect the vertical distribution of SOC, suggesting that preferential C allocation in root systems and their adequate vertical distributions enhance SOC accrual in deeper layers. Moreover, Bai et al. (2020) reported that root cellulose is the primary driving factor to the changes of SOC sequestration in grassland restoration. Our study reveals that vertical variations in SOC distribution for the same plant species may be influenced by additional factors contributing to carbon deposition at depth.

3.5 Conclusions

This study demonstrated that SOC stocks in tropical sandy soils of the Pontal do Paranapanema region are significantly influenced by both soil type and land use. In Ultisols, the highest SOC stocks were observed under forest restoration and sugarcane, while in Oxisols, native forest fragments and pastures showed the greatest SOC stocks. Consequently, our initial hypothesis that forest restoration on sandy soils (Ultisols and Oxisols) would exhibit greater potential for carbon sequestration than under other agricultural land uses was not fully supported by our results, especially due to the high SOC stocks under sugarcane, a perennial crop with high biomass accretion, and to the relatively low stocks for forest restoration in Oxisols.

Although cassava cultivation was the most SOC-depletive system, our findings indicate that different land uses promote SOC accretion and depletion differently among soil classes, thus rejecting our second hypothesis as well. The SOC stock gap between the two soil types under forest restoration shows the importance of edaphic factors such as structural patterns leading to considerable differences in soil bulk density and SOC allocation in subsoil. Our results also suggest that management practices should be tailored to specific soil types to optimize carbon sequestration. These steps are crucial for developing effective land management practices that enhance SOC storage and contribute to mitigating climate change impacts in tropical sandy soils.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper entitled: Organic carbon stocks across various land use systems in sandy Ultisols and Oxisols in Brazil.

Acknowledgments

We acknowledge the financial support of China Three Gorges Corporation (CTG-Brazil), Coordination of Improvement of Higher Education Personnel (CAPES), National Council for Scientific and Technological Development (CNPq) process 406903/2022-0, Foundation for Research Support of the State of Minas Gerais (FAPEMIG) process APQ-01173-24, and Institute for Ecological Research (IPÊ). YLZ, SHGS, BMS, FAB and JCA thank CNPq for grants number 308235/2022-3, 307532/2022-4, 311743/2021-8, 174948/2023-9, and 307059/2022-7, respectively.

4 REFERENCES

Anderson-Teixeira, K.J., Davis, S.C., Masters, M.D., Delucia, E.H., 2009. Changes in soil organic carbon under biofuel crops. GCb Bioenergy 1, 75–96. https://doi.org/10.1111/j.1757-1707.2008.01001.x.

Babu, S., Mohapatra, K.P., Yadav, G.S., Lal, R., Singh, R., Avasthe, R.K., Das, A., Chandra, P., Gudade, B.A., Kumar, A., 2020 Soil carbon dynamics in diverse organic land use systems in North Eastern Himalayan ecosystem of India. Catena 194, 104785, https://doi.org/10.1016/j.catena.2020.104785.

Bai, X., Guo, Z., Huang, Y., Na, S., 2020. Root cellulose drives soil fulvic acid carbon sequestration in the grassland restoration process. Catena 191, 104575. https://doi.org/10.1016/j.catena.2020.104575.

Benevenute, P.A.N. Morais, E.G. Souza, A.A. Vasques, I.C.F. Cardoso, D.P. Sales, F. R. Severiano, E.C. Homem, B.G.C. Casagrande, D.R. Silva B.M. Penetration resistance: An effective indicator for monitoring soil compaction in pastures. Ecological Indicators, 117 (2020), p. 106647, 10.1016/j.ecolind.2020.106647

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Klute, A. (Ed.), Methods of Soil Analysis, American Society of Agronony, Madison (1986), pp. 363375.

Bócoli, F.A., Santos, W.J.R., Silva, S.H.G., Teixeira, A.F.S., Mancini, M., Curi, N., 2021. Study of an abnormal occurrence of Oxisols in strongly undulated relief in the south of Minas Gerais, Brazil, with support of pXRF and geomorphology. Ciênc. Agrotec. 45, e018121. https://doi.org/10.1590/1413-7054202145018121.

Carvalho, J.L.N., Raucci, G.S., Cerri, C.E.P., Bernoux, M., Feigl, B.J., Wruck, F.J., Cerri., C.C., 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil Till. Res. 110, 175–186. https://doi.org/10.1016/j.still.2010.07.011.

Cherubin, M.R., Oliveira, D.M.S., Feigl, B., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., Varanda, L.L., Morais, M.C., Satiro, L.S., Popin, G.V., Paiva, S.R., Santos, A.K.B., Vasconcelos, A.L.S., Melo, P.L.A., Cerri, C.E.P., Cerri, C.C., 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. Sci. Agric. 75(3), 255–272. https://doi.org/10.1590/1678-992X-2016-0459.

Figueiredo, P.G., Bicudo, S.J., Chen, S., Fernandes, A.M., Tanamati, F.Y., Djabou-Fondjo, A.S.M., 2017. Effects of tillage options on soil physical properties and cassava-dry-matter partitioning. Field Crops Res 204, 191–198. https://doi.org/10.1016/j.fcr.2016.11.012

Freitas, L.D., Oliveira, I.A.D., Casagrande, J.C., Silva, L.S., Campos, M.C.C., 2018. Estoque de carbono de Latossolos em sistemas de manejo natural e alterado. Ci. Fl. 28, 228–239. https://doi.org/10.5902/1980509831575.

Freitas, L. D., Oliveira, I.A.D., Casagrande, J.C., Silva, L.S., Campos M.C.C. Estoque de carbono de Latossolos em sistemas de manejo natural e alterado. Ci. Fl., 28 (2018), pp. 228-239, 10.5902/1980509831575.

Gee, G.W., Or, D., 2002. Particle-size analysis. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Physical Methods. SSSA Book Series No. 5 Soil Sci. Soc. Am, Madison, pp. 255–289.

Haghverdi, K., Kooch, Y., 2019. Effects of diversity of tree species on nutrient cycling and soil-related processes. Catena 178, 335–344. https://doi.org/10.1016/j.catena.2019.03.041.

Instituto Brasileiro de Florestas. 2024. Bioma Mata Atlântica. Available at: https://www.ibflorestas.org.br/bioma-mata-atlantica?utm_source=google-ads&utm_medium=cpc&utm_campaign=biomas&keyword=mata%20atlantica&creative=519561022233&gad_source=1&gclid=CjwKCAjw_Na1BhAlEiwAM-dm7J_3cUebemDeXgOl6BmFmQXj-BN7ejIoLfviXJ-j6ZAxrRlhWDzv4hoCT3sQAvD_BwE. Acess in: July 27th, 2024.

James, J.N., Gross, C.D., Dwivedi, P., Myers, T., Santos, F., Bernardi, R., Butman, D., 2019. Land use change alters the radiocarbon age and composition of soil and water-soluble organic matter in the Brazilian Cerrado. Geoderma, 345, 38–50. https://doi.org/10.1016/j.geoderma.2019.03.019.

Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10(2), 423–436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2.

Joly, C.A., Metzger, J.P., Tabarelli, M., 2014. Experiences from the Brazilian Atlantic Forest: ecological findings and conservation initiatives. New Phytol. 204(3), 459–473. https://doi.org/10.1111/nph.12989.

Koga, N., Shimoda, S., Shirato, Y., Kusaba, T., Shima, T., Niimi, H., Yamane, T., Wakabayashi, K., Niwa, K., Kohyama, K., Obara, H., Takata, Y., Kanda, T., Inoue, H., Ishizuka, S., Kaneko, S., Tsuruta, K., Hashimoto, S., Shinomiya, T., Aizawa, S., Ito, E., Hashimoto, T., Morishita, T., Noguchi, K., Ono, K., Katayanagi, N., Atsumi, K., 2020. Assessing changes in soil carbon stocks after land use conversion from forest land to agricultural land in Japan. Geoderma 377, 114487. https://doi.org/10.1016/j.geoderma.2020.114487.

Lal, R., 2004. Soil carbon sequestration impacts global climate change and food security. Science. 304, 5677, 1623–1627. https://doi.org/10.1126/science.1097396

Le, K.N., Jha, M.K., Reyes, M.R., Jeong, J., Doro, L., Gassman, P.W., Hok, L., Sá, J.C.M., Boulakia, S., 2018. Evaluating carbon sequestration for conservation agriculture and tillage systems in Cambodia using the EPIC model. Agr. Ecosyste. Environ. 251, 37–47. https://doi.org/10.1016/j.agee.2017.09.009.

Leal, M.R.L.V., Galdo, M.V., Scarpare, F.V., Seabra, J.E.A., Walter, A., Oliveira, C.O.F., 2013. Sugarcane straw availability, quality, recovery and energy use: a literature review. Biomass Bioenerg. 53, 11–19. https://doi.org/10.1016/j.biombioe.2013.03.007.

Ledo, A., Smith, P., Zerihun, A., Whitaker, J., Vicente-Vicente, J. L., Qin, Z., McNamara, N. P., Zinn, Y. L., Llorente, M., Liebig, M., Kuhnert, M., Dondini, M., Don, A., Diaz-Pines, E., Datta, A., Bakka, H., Aguilera, E., Hillier, J., 2020. Changes in soil organic carbon under perennial crops. Global Change Biol. 26, 4158-4168. https://doi.org/10.1038/s41597-019-0062-1

Mantovani, V.A., Terra, M.D.C.N.S., Rodrigues, A.F., Silva, C.A., Guo, L., de Mello, J.M., Mello, C.R., 2024. Unprecedentedly high soil carbon stocks and their spatial variability in a seasonally dry Atlantic Forest in Brazil. Catena 235, 107696. https://doi.org/10.1016/j.catena.2023.107696.

Mendes, L.M., César, R.G., Uezu, A., Beltrame, T.P., Rodriguez, L.C., Gomes, H.B., Cullen, L., 2021. Largecanopy and animal-dispersed species facilitatenatural regeneration in tropical forest restoration. Restorat. Ecol. 29, e13406. https://doi.org/10.1111/rec.13406.

Moraes, J.D., Neill, C., Volkoff, B., Cerri, C.C., Melillo, J., Lima, V.C., Steudler, P.A., 2002. Soil carbon and nitrogen stocks following forest conversion to pasture in the Western Brazilian Amazon Basin. Acta Sci. 24(5), 1369–1376.

Nelson, D.W., Sommers, L.E., Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A.,Johnston C.T., Sumner M.E. (Eds.), Method of Soil Analysis, Part 3, 34, American Society of Agronomy (1996), pp. 961-1010

Padbhushan, R., Kumar, U., Sharma, S., Rana, D.S., Kumar, R., Kohli, A., Kumari, P., Parmar, B., Kaviraj, M., Sinha, A.K., Annapurna, K., Gupta, V.V.S.R., 2022. Impact of Land-Use Changes on Soil Properties and Carbon Pools in India: A Meta-analysis. Front. Environ. Sci. 9, 794866. https://doi.org/10.3389/fenvs.2021.794866.

Pádua, E.J., Guerra, A.R., Zinn, Y.L. 2015. Modeling bulk density of subsoil under native vegetation in Minas Gerais, Brazil. R. Bras. Ci. Solo 39, 725–736. http://dx.doi.org/10.1590/01000683rbcs20140028.

Peixoto, D.S., Silva, B.M., Oliveira, G.C., Moreira, S.G., Silva F. A soil compaction diagnosis method for occasional tillage recommendation under continuous no tillage system in Brazil. Soil Till. Res., 194 (2019), p. 104307, 10.1016/j.still.2019.104307.

Quaggio, J.A. Van Raij, B. Determinação do pH em cloreto de cálcio e da acidez total. Análise química para avaliação da fertilidade de solos tropicais. Instituto Agronômico de Campinas, Campinas (2001), pp. 181-188.

Rittl, T.F., Oliveira, D., Cerri, C.E.P., 2017. Soil carbon stock changes under different land uses in the Amazon. Geoderma Reg. 10, 138–143. https://doi.org/10.1016/j.geodrs.2017.07.004.

Rossi, M. 2017. Mapa pedológico do Estado de São Paulo: revisado e ampliado. São Paulo: Instituto Florestal. V.1. 118p.

Santos, C.A., Rezende, C.D.P., Pinheiro, É.F.M., Pereira, J.M., Alves, B.J., Urquiaga, S., Boddey, R.M., 2019. Changes in soil carbon stocks after land-use change from native vegetation to pastures in the Atlantic Forest region of Brazil. Geoderma 337, 394–401. http://dx.doi.org/10.1016/j.geoderma.2018.09.045.

Signor, D., Zani, C.F., Paladini, A.A., Deon, M.D., Cerri, C.E.P., 2014. Estoques de carbono e qualidade da matéria orgânica do solo em áreas cultivadas com cana-de-açúcar. Rev. Bras. Ci. Solo, 38, 1402–1410. https://doi.org/10.1590/S0100-06832014000500005.

Silva, A.J.P., Lopes, R.C., Vasconcelos, A.M., Bahia, R.B.C., 2003. Bacias Sedimentares Paleozóicas e Meso Cenozóicas Interiores In: Bizzi, L.A., Schobbenhaus, C., Vidotti, R.M., Gonçalves, J.H. Geologia, tectônica e recursos minerais do Brasil: texto, mapas SIG. Brasília: CPRM – Serviço Geológico do Brasil.

Siqueira Neto, M., Piccolo, M.D.C., Scopel, E., Costa Junior, C.D., Cerri, C.C., Bernoux, M., 2009. Carbono total e atributos químicos com diferentes usos do solo no Cerrado. Acta Sci. Agron. 31, 709–717. https://doi.org/10.4025/actasciagron.v31i4.792.

Souza, C.R., Maia, V.A., de Aguiar-Campos, N., Santos, A.B.M., Rodrigues, A.F., Farrapo, C.L., Gianasi, F.M., de Paula, G.G.P., Fagundes, N.C.A., Silva, W.B., Santos, R.M., 2021. Long-term ecological trends of small secondary forests of the atlantic forest hotspot: A 30-year study case. For. Ecol. Manag. 489, 119043, https://doi.org/10.1016/j.foreco.2021.119043.

Terra, M.C.N.S., Nunes, M.H., Souza, C.R., Ferreira, G.W.D., Prado-Junior, J.A. do, Rezende, V.L., Maciel, R., Mantovani, V., Rodrigues, A., Morais, V.A., Scolforo, J.R.S., Mello, J.M., 2023. The inverted forest: Aboveground and notably large influence soil carbon sequestration? Geoderma 137, 253–268. https://doi.org/10.1016/j.geoderma.2006.09.003.

Thomaz, E.L., Kurasz, J.P., 2023. Long Term of Soil Carbon Stock in No-Till System Affected by a Rolling Landscape in Southern Brazil. Soil Systems, 7(2), 60. https://doi.org/10.3390/soilsystems7020060.

Uezu, A., Metzger, J.P., 2016. Time-Lag in Responses of Birds to Atlantic Forest Fragmentation: Restoration Opportunity and Urgency. PLoS ONE 11, e0147909. https://doi.org/10.1371/journal.pone.0147909.

Walkley, A., & Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science 37, 29–38. https://doi.org/10.1097/00010694-193401000-00003.

Yang, S., Dong, Y., Song, X., Wu, H., Zhao, X., Yang, J., Chen, S., Smith, J., Zhang, G. L., 2022. Vertical distribution and influencing factors of deep soil organic carbon in a typical subtropical agricultural watershed. Agri. Ecosyst. Environ. 339, 108141. https://doi.org/10.1016/j.agee.2022.108141.

Yang, Y., Tilman, D., Furey, G., Lehman, C., 2019. Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nat. Commun. 10, 718 https://doi.org/10.1038/s41467-019-08636-w.

Zanini, A.M., Mayrinck, R.C., Vieira, S.A., de Camargo, P.B., Rodrigues, R.R., 2021. The effect of ecological restoration methods on carbon stocks in the Brazilian Atlantic Forest. Forest Ecol. Manag. 481, 118734 https://doi.org/10.1016/j.foreco.2020.118734.

Zanini, A.M., Mayrinck, R.C., Vieira, S.A., de Camargo, P.B., Rodrigues R.R. The effect of ecological restoration methods on carbon stocks in the Brazilian Atlantic Forest. Forest Ecol. Manag., 481 (2021), Article 118734, 10.1016/j.foreco.2020.118734.

Zinn, Y.L., Andrade, A.B., Araujo, M.A., Lal, R., 2018. Soil organic carbon retention more affected by altitude than texture in a forested mountain range in Brazil. Soil Res. 56(3), 284–295. https://doi.org/10.1071/SR17205.

Zinn, Y.L., Lal, R., Resck, D.V., 2005. Changes in soil organic carbon stocks under agriculture in Brazil. Soil Tillage Res. 84(1), 28–40. https://doi.org/10.1016/j.still.2004.08.007.

5 Supplementary data

Table S 1. Land use history in the Pontal do Paranapanema region.

<table>
<tr><th>Locations</th><th>Soil</th><th>2023</th><th>2021</th><th>2019</th><th>2017</th><th>2015</th><th>2013</th></tr>
<tr><td>1</td><td>Ultisol</td><td colspan="6">Restoration</td></tr>
<tr><td>2</td><td>Ultisol</td><td colspan="4">Restoration</td><td colspan="2">Pasture</td></tr>
<tr><td>3</td><td>Ultisol</td><td colspan="6">Restoration</td></tr>
<tr><td>4</td><td>Oxisol</td><td colspan="4">Restoration</td><td colspan="2">Pasture</td></tr>
<tr><td>5</td><td>Oxisol</td><td colspan="6">Restoration</td></tr>
<tr><td>6</td><td>Oxisol</td><td colspan="6">Restoration</td></tr>
<tr><td>7</td><td>Ultisol</td><td colspan="6">Pasture</td></tr>
<tr><td>8</td><td>Ultisol</td><td colspan="6">Pasture</td></tr>
<tr><td>9</td><td>Ultisol</td><td colspan="6">Pasture</td></tr>
<tr><td>10</td><td>Oxisol</td><td colspan="6">Pasture</td></tr>
<tr><td>11</td><td>Oxisol</td><td colspan="6">Pasture</td></tr>
<tr><td>12</td><td>Oxisol</td><td colspan="6">Pasture</td></tr>
<tr><td>13</td><td>Ultisol</td><td colspan="6">Sugarcane</td></tr>
<tr><td>14</td><td>Ultisol</td><td colspan="6">Sugarcane</td></tr>
<tr><td>15</td><td>Ultisol</td><td colspan="6">Sugarcane</td></tr>
<tr><td>16</td><td>Oxisol</td><td colspan="6">Sugarcane</td></tr>
<tr><td>17</td><td>Oxisol</td><td colspan="4">Sugarcane</td><td colspan="2">Pasture</td></tr>
<tr><td>18</td><td>Oxisol</td><td colspan="6">Sugarcane</td></tr>
<tr><td>19</td><td>Ultisol</td><td colspan="4">Annual crop</td><td colspan="2">Sugarcane</td></tr>
<tr><td>20</td><td>Ultisol</td><td colspan="2">Annual crop</td><td colspan="4">Sugarcane</td></tr>
<tr><td>21</td><td>Ultisol</td><td colspan="3">Annual crop</td><td colspan="3">Pasture</td></tr>
<tr><td>22</td><td>Oxisol</td><td colspan="4">Annual crop</td><td colspan="2">Sugarcane</td></tr>
<tr><td>23</td><td>Oxisol</td><td colspan="4">Annual crop</td><td colspan="2">Pasture</td></tr>
<tr><td>24</td><td>Oxisol</td><td colspan="2">Annual crop</td><td colspan="4">Pasture</td></tr>
<tr><td>25</td><td>Ultisol</td><td colspan="2">Cassava</td><td colspan="4">Pasture</td></tr>
<tr><td>26</td><td>Ultisol</td><td colspan="2">Cassava</td><td colspan="4">Pasture</td></tr>
<tr><td>27</td><td>Ultisol</td><td colspan="3">Cassava</td><td colspan="3">Pasture</td></tr>
<tr><td>28</td><td>Oxisol</td><td colspan="3">Cassava</td><td colspan="3">Pasture</td></tr>
<tr><td>29</td><td>Oxisol</td><td colspan="2">Cassava</td><td colspan="4">Pasture</td></tr>
<tr><td>30</td><td>Oxisol</td><td colspan="2">Cassava</td><td colspan="4">Pasture</td></tr>
<tr><td>31</td><td>Ultisol</td><td colspan="6">Fragment</td></tr>
<tr><td>32</td><td>Ultisol</td><td colspan="6">Fragment</td></tr>
<tr><td>33</td><td>Ultisol</td><td colspan="6">Fragment</td></tr>
<tr><td>34</td><td>Oxisol</td><td colspan="6">Fragment</td></tr>
<tr><td>35</td><td>Oxisol</td><td colspan="6">Fragment</td></tr>
<tr><td>36</td><td>Oxisol</td><td colspan="6">Fragment</td></tr>
</table>

Table S 2. Statistical analysis of the soil type and land use factor.

Factor	Clay	Sand	Silt	Bd	pH	K	P	Al	CEC
	------------ % ------------			g cm^{-3}		---- mg dm^{-3}----		--- cmol$_c$ dm^{-3}---	
					0–20 cm				
Land use X Soil type	p=0.66	p=0.56	p=0.17	p=0.34	p=0.98	p=0.61	p=0.77	p=0.81	p=0.28
Land use									
Sugarcane	21.1 a	74.5 a	4.5 a	1.64 a	5.9 a	8.1 a	25.1 a	0.13 b	4.7 a
Fragment	18.9 ab	77.1 a	4.8 a	1.24 b	6.1 a	24.3 a	1.6 a	0.40 a	4.6 a
Annual crop	16.3 ab	78.8 a	3.9 a	1.59 a	4.9 a	51.9 a	14.7 a	0.13 b	4.2 a
Restoration	14.5 ab	82.5 a	3.8 a	1.50 a	5.3 a	44.1 a	3.6 a	0.23 ab	3.9 a
Cassava	11.5 ab	84.6 a	4.5 a	1.56 a	5.8 a	2.3 a	2.2 a	0.10 b	2.5 a
Pasture	10.5 b	85.1 a	2.9 a	1.51 a	4.8 a	8.7 a	2.4 a	0.10 b	3.2 a
	p=0.02	p=0.20	p=0.89	p<0.01	p=0.07	p=0.08	p=0.09	p=0.01	p<0.01
Soil type									
Ultisol	14.1 a	82.1 a	3.7 a	1.52 a	5.5 a	28.5 a	5.5 a	0.16 a	3.9 a
Oxisol	16.8 a	78.7 a	4.4 a	1.50 a	5.4 a	17.9 a	11.1 a	0.21 a	3.8 a
	p=0.16	p=0.14	p=0.48	p=0.59	p=0.91	p=0.36	p=0.31	p=0.38	p=0.75
CV (%)	36.2	9.7	73.2	7.5	15.7	147.5	194.9	81.3	23.8
					80–100 cm				
Land use X Soil type	p=0.49	p=0.40	p=0.44	p=0.24	p=0.92	p=0.42	p=0.77	p=0.25	p=0.55
Land use									
Sugarcane	27.6 a	67.0 a	5.3 a	1.55 a	5.1 a	4.8 a	0.6 a	0.22 a	2.9 a
Fragment	22.7 a	70.9 a	4.0 a	1.33 b	4.9 a	12.6 a	0.8 a	0.50 a	2.7 a
Annual crop	25.1 a	73.8 a	3.5 a	1.57 a	5.2 a	8.7 a	2.0 a	0.28 a	2.7 a
Restoration	17.3 a	72.0 a	2.5 a	1.62 a	5.2 a	24.3 a	1.2 a	0.23 a	2.5 a
Cassava	18.4 a	79.6 a	3.1 a	1.54 a	5.2 a	2.3 a	0.2 a	0.15 a	2.1 a
Pasture	25.5 a	77.2 a	4.4 a	1.52 a	5.7 a	1.0 a	0.4 a	0.13 a	2.3 a
	p=0.07	p=0.09	p=0.49	p<0.01	p=0.44	p=0.35	p=0.46	p=0.06	p=0.26
Soil type									
Ultisol	21.8 a	75.1 a	3.1 a	1.56 a	5.2 a	13.3 a	0.6 a	0.26 a	2.5 a
Oxisol	23.8 a	71.7 a	4.5 a	1.49 a	5.3 a	4.7 a	1.1 a	0.24 a	2.6 a
	p=0.37	p=0.18	p=0.11	p=0.08	p=0.69	p=0.20	p=0.43	p=0.81	p=0.74
CV (%)	28.9	10.2	67.4	6.8	11.7	217.1	189.6	82.6	24.1

Averages followed by different letters mean that the land uses differed from each otherat 5% probability using the Tukey test ($p < 0.05$).

Article 2 - Written in accordance with scientific journal standards - Preliminary version	
Article title:	Impact of soil uses on ecosystem services in Brazilian Atlantic rainforest biome indices
authors:	Maria Cecília Vieira Totti Sérgio Henrique Godinho Silva Bruno Montoani Silva Fernanda Almeida Bócoli Vanêssa Lopes de Faria Adriana Marcela Silva-Olaya Andrés Olaya Montes Alexandre Uezu Laury Cullen Junior Vinícius Ferreira Fernandes Junior Cesar Avanzi
Periódico:	Ecosystem Services
ISSN	2212-0416
DOI	https://www.sciencedirect.com/journal/ecosystem-services

PAPER 2 - IMPACT OF SOIL USES ON ECOSYSTEM SERVICES IN BRAZILIAN ATLANTIC RAINFOREST BIOME INDICES

Maria Cecília Vieira Totti[1,2]; Sérgio Henrique Godinho Silva[1]; Bruno Montoani Silva[1]; Fernanda Almeida Bócoli[1]; Vanêssa Lopes de Faria[1]; Adriana Marcela Silva-Olaya[2]; Andrés Olaya Montes[1,2]; Alexandre Uezu[3]; Laury Cullen Junior[3]; Vinícius Ferreira Fernandes[4]; Junior Cesar Avanzi[1*]

[1] Department of Soil Science, Federal University of Lavras, Lavras, Minas Gerais 37203-202, Brazil

[2]Amazonian Research Center CIMAZ-MACAGUAL, University of the Amazon, Florencia 180002, Colombia

[3] Institute for Ecological Research, Faculty for Environmental Conservation and Sustainability, Nazaré Paulista, São Paulo 12960-000, Brazil

[4] Soil and Fertilizer Research Center, Agronomic Institute of Campinas, Campinas, São Paulo 13020-902, Brazil

* **Corresponding author**. E-mail: junior.avanzi@ufla.br (J. C. Avanzi).

Highlights

- Land use directly affects the soil's ability to provide ecosystem services.

- Forest restoration helps recover sustainability and mitigate climate change.
- Restoration and sugarcane improve the supply of ecosystem services.
- Intensive cassava cropping harms soil fertility and structure.
- Carbon cycling and fertility show synergies; intensive use shows trade-offs.
- The index supports sustainable soil management in tropical regions.

Abstract

Soils are essential in providing ecosystem services and fundamental for environmental sustainability and climate change mitigation. With this in mind, this study aimed to propose an index of soil ecosystem services, under different uses, focused on the physical quality of the main soil classes in the Brazilian Atlantic Rainforest biome. The study assessed the ES provided by two soil classes (Ultisols and Oxisols) under different land uses in the Atlantic Rainforest biome (forest fragment, forest restoration, pasture, sugarcane, cassava, and annual crop) on Pontal do Paranapanema, Brazil. The proposed ecosystem services index considered the indicators of carbon sequestration, carbon cycling, soil fertility, soil structure, and water regulation. The results showed that, when well-managed, uses such as forest restoration and sugarcane presented a greater capability to provide ES. Intensive cultivation, such as cassava, had a negative impact on soil fertility and structure. There were synergies between carbon cycling and fertility, while compensations appeared in intensive uses, confirming the need for proper soil management. Finally, the ecosystem services index was presented as a strategic tool for supporting sustainable soil management in tropical regions, such as the Atlantic Rainforest biome.

Keywords: sustainability; Oxisol; Ultisol; soil carbon; forest restoration; forest fragment

1 Introduction

Soil is an essential element of natural capital, performing ecological functions that underpin the provision of several ecosystem services (ES) (Smith et al., 2021). Beyond its fundamental role in supporting agricultural production, soil also filters and purify water, regulates hidrological flows, host the soil biota responsible for decomposition and nutrient cycling, and acts as a significant carbon reservoir, storing app the found in the supplies physical support for infrastructure and human activities (Jónsson et al., 2017).

However, the capacity of soil to perform these vital ecological functions is strongly influenced by site-specific natural factors, including climate, topography, soil type, as well as land use management practices (Hyun et al., 2022; Adhikari and

Hartemink, 2016; Silva-Olaya et al., 2022). Changes in land cover and soil management can significantly promote or hinder the supply of ES (Foley et al., 2005). In agricultural soil, the intensive practices used for food production threaten the soil´s long-term capacity of soil to deliver essential ecosystem services, thereby compromising the sustainability of ecosystems and communities (FAO, 2017).

This scenario is particularly relevant in countries such as Brazil, one of the largest global food producers (REF), where economic pressures have driven extensive land conversion to intensive agricultural and livestock production systems (REF). Although some studies have evaluated structural and governance-related determinants influencing the adoption of sustainable agricultural practices in Brazil (Latawiec *et al.*, 2017) (Latawiec et al., 2017; ADD REF), There remains a paucity of studies focusing on the impact of these agricultural systems on soil-related ES. Previous research has predominantly examined how different land use systems affect individual soil physical, chemical, and biological properties in tropical regions (ADD REF). However, comprehensive evaluations considering multiple soil ES remain scarce, despite their importance for guiding sustainable land management policies and practices.

In this study, we employed a comprehensive approach to assess the provision of four critical soil ES —carbon sequestration, carbon cycling, soil fertility, and soil structure and water regulation—in six representative agricultural land-use systems located in Central Brazil across two major Brazilian soil classes. Specifically, our objectives were to (i) evaluate how different agricultural systems influence the soil's capacity to support these key soil ES, ii) to identify potential synergies and trade-offs among these services. We hypothesized that conservation-oriented agricultural systems result in higher overall provision of soil ecosystem services compared to conventional intensive agricultural systems, regardless of the soil type.

2 Material and methods

2.1 Study area

The study was performed in southwest Brazil, specifically at the Pontal do Paranapanema region, located at the westernmost part of the State of São Paulo (Fig. 1). According to the Köppen climate classification, there are two types of climates in the region, Aw (tropical savanna) and Cwa (humid subtropical). Throughout the year, the temperature usually varies from 11ºC to 37ºC, with an average annual rainfall of around 1,500 mm, mainly concentrated from December to February (summer), with a dry period in winter. The region is part of the Atlantic Rainforest biome, which covers most of

Brazil's eastern coastline, in stretches that extend hundreds of kilometers into the continent. Geologically, the area is made up of basaltic flows from the Serra Geral Formation, overlain by aeolian sandstones from the Botucatu Formation. The local altitude varies between 350 and 560 meters above sea level (Silva et al., 2003).

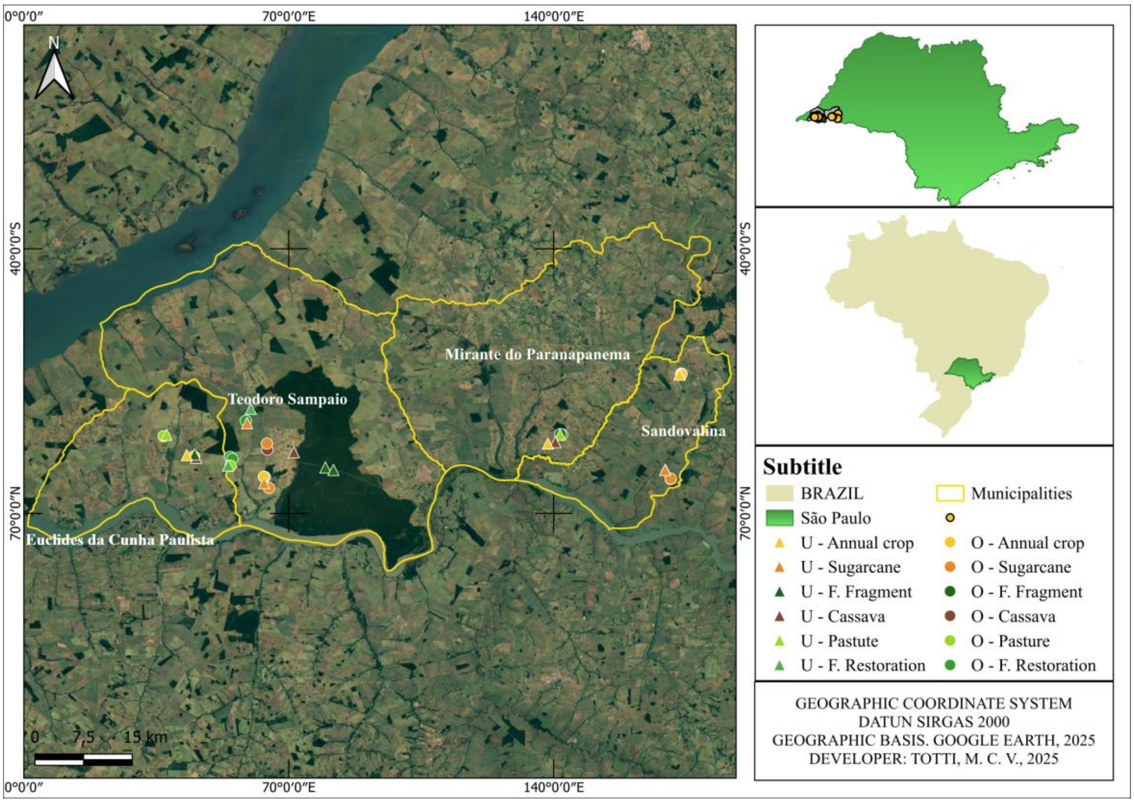


Fig. 1. Location of soil samples in the Pontal do Paranapanema region, São Paulo, Brazil.

Soil sampling was performed over the two main soil classes in the region i.e. Oxisols and Ultisols (Table 1). In each soil class, six land use systems were studied: 1) native forest fragments (Semideciduous Forest); 2) secondary forest restoration; 3) pastures featuring terraces as a conservation practice; 4) sugarcane, 5) cassava, and 6) annual crop rotations (soybean/corn) (Fig. 2). The secondary forest restorations are aged 15–20 years, and were established by planting seedlings of local native species, aiming the preservation of the original genetic pool (Mendes et al., 2021) (Fig 2). The soil particle size distribution to a depth of 0.20 m in each land use system is presented in Table 1.

Table 1. Average results of the physical characterization of soils in the study area.

		Ultisol			Oxisol		
Use	Depth	Clay	Silt	Sand	Clay	Silt	Sand
		-----(%)-----					
Fragment	0.00-0.20	16.6	1.4	82.1	21.4	6.5	72.1
Restoration	0.00-0.20	16.7	4.0	79.2	12.3	1.7	85.9
Pasture	0.00-0.20	8.0	4.2	87.8	12.9	4.9	82.3
Sugarcane	0.00-0.20	18.6	4.3	77.1	23.6	4.6	71.8

Cassava	0.00-0.20	10.7	2.1	87.2	12.4	5.5	82.1
Annual crop	0.00-0.20	14.2	6.3	79.5	18.4	3.3	78.3

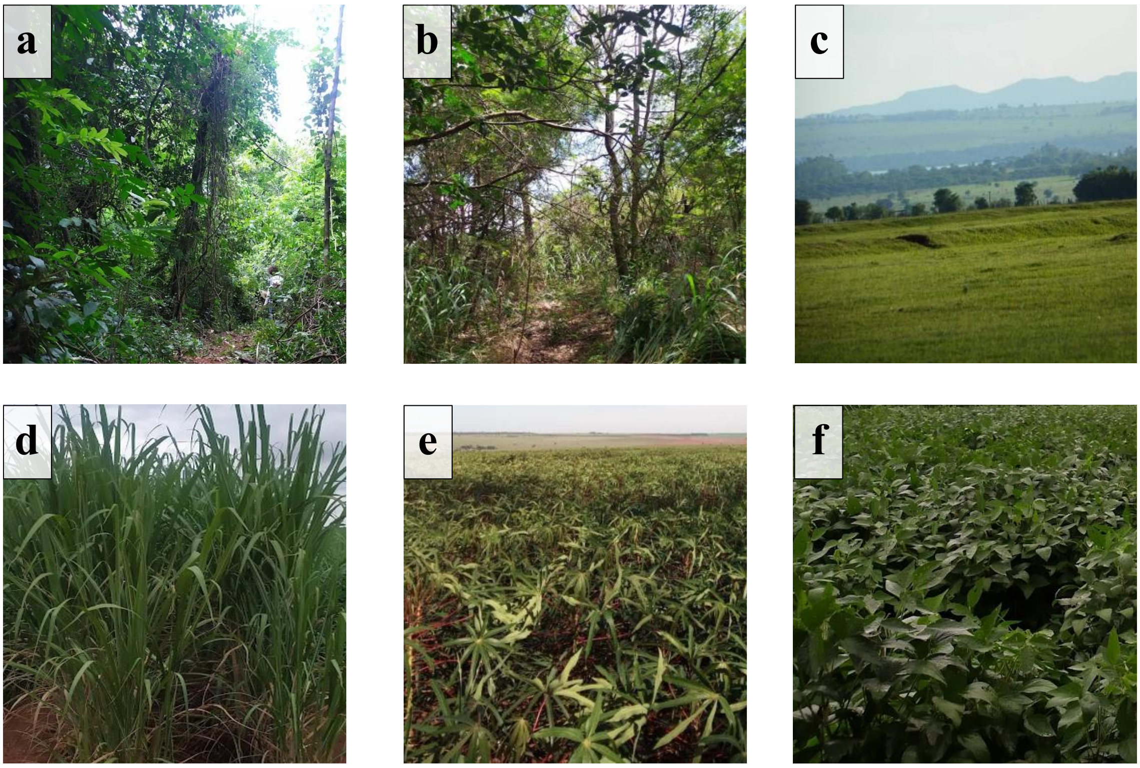


Fig. 2. Most common soil uses in the Pontal do Paranapanema region. a) forest fragment; b) secondary forest (restoration) c) pasture, d) sugarcane, e) cassava, e f) annual crop.

2.2 Sampling and data collection

Soil samples were collected in February 2023. Three sampling points were established across each land use system studied per each soil class, totalling 36 sampling points in the study area. Then, soil cores (3 cm diameter x 5 cm depth and 8 cm diameter x 5 cm depth) were collected in each sampling plot at the soil layer 0 – 20 cm depth for the analyses of physical properties with preserved structure. Disturbed soil samples were also collected for chemical and biological analyses. In addition to the analysis of soil resistance to penetration and water infiltration rate, it is carried out in situ.

Following the framework used by Silva-Olaya et al. (2022), which connects key soil properties to ecosystem services through soil functions, we measured X physical soil properties and X biochemical properties related to soil chemical fertility and hydrological functions.

Undisturbed soil samples were used to assess soil physical properties. Soil bulk density was determined by the ratio between the mass and volume of dry soil (Blake e Hartge, 1986). Soil porosity was determined using the table tension method, applying 6 kPa to the saturated samples to determine macroporosity, followed by drying the samples in an oven at 105ºC and weighing to obtain total porosity. Microporosity was calculated by the difference between total porosity and macroporosity (Teixeira et al., 2017).

The mean weight diameter (MWD) and geometric mean diameter (GMD) of the aggregates were assessed using Yoder wet sieving (Kemper and Chepil, 1965). Soil resistance to penetration (RP) was evaluated in the field with an impact penetrometer (Stolf et al., 2014). The constant head permeameter assessed saturated conductivity (Ks) (Klute and Dirksen, 2018). The soil water infiltration rate was assessed using the Mini Disk Infiltrometer (Zhang, 1997).

Distrubed soil samples were sieved (2 mm), ground, and air-dried for further biochemical analysis. Soil pH ($CaCl_2$ 0,01 mol L^{-1}), available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), sodium (Na), potential acidity (H+Al), the sum of exchangeable basis (SB), bases saturation index (V), cation exchange capacity at pH = 7 (CTC), cation effective exchange capacity (t), aluminum saturation (m), P-remaining (P-rem), and organic matter (OM) were carried out according to Teixeira et al. (2017).

The concentrations of soil organic carbon (SOC) were determined by dry combustion using an elemental analyzer (Flash EA1112, Thermo Electron Corporation, Milan, Italy), following the method described by Nelson and Sommers (1996). Soil carbon stocks were calculated following the analytical methods reported by Totti et al. (2025). The fractionation of organic matter into particulate fraction and mineral fraction was carried out following the methodology of Leuthold et al. (2023).

β-Glycosidase was assessed according to Dick et al. (2015). Microbial biomass carbon (MBC) and soil basal respiration (SBR) were assessed according to the methodology of Mendonça and Matos (2005). The metabolic quotient (qCO2) was determined from basal soil respiration and microbial biomass carbon (Anderson and Domsch, 1993).

2.3 Soil ecosystem services assessment

Soil physical and biochemical properties were used as indicators to develop sub-indices of four soil ecosystem services: SE 1 - carbon sequestration; SE 2 - carbon cycling; SE 3 - soil structure and water regulation; SE 4 - soil fertility. These sub-indices were then combined to create an overall SES index for each land use system studied.

The ecosystem services (ES) analyzed in this study were categorized based on their respective soil functions, acknowledging that many services arise from the synergistic interaction of multiple ecological functions. For ES1, related to carbon sequestration, it was considered a supporting ecological function, essential for the regulation of the climate. Indicators used for this service included total soil carbon stock, soil organic carbon content, and its fractions (particulate organic matter – POM and mineral-associated organic matter – MAOM), in addition to microbial biomass carbon. For SE 2, the carbon cycling was framed as a process underpinning both soil fertility support and climate regulation, as it directly influences the accumulation, stability, and quality of soil organic matter. To assess this function, we used β-glucosidase activity (a key enzyme in cellulose degradation) and basal respiration (an indicator of active microbial metabolism).

For the SE 3 - soil fertility service, we selected chemical attributes such as pH, potassium (K), phosphorus (P), calcium (Ca), magnesium (Mg), cation exchange capacity at pH 7.0 (CEC), and available nitrogen and phosphorus, all of which are directly associated with agricultural productivity and the support of natural vegetation. Finally, for the SE 4 - soil structure and water regulation service, indicators related to soil aggregation were adopted, including the mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates. Additionally, macroporosity, microporosity, total porosity, bulk density, and soil penetration resistance were included, as they reflect the soil's capacity to infiltrate and retain water, resist erosion, and sustain biological activity. For the water movement function, infiltration rate and saturated hydraulic conductivity (Ks) were used.

Table 2 illustrates the mechanisms by which land use affects the soil's capacity to provide those ecosystem services (ES). Thus, justification was inserted into the choice of these services. There is a flowchart in Fig. 3 with the attributes used as indicators for each assessed ES. It is important to note that the evaluated attributes are not direct measures of ES, but they represent the soil's capability of providing ES (Silva-Olaya et al., 2022).

Table 2. Selected ecosystem services related to soil, impact mechanisms due to the change of land use, and justification for choosing this service.

Soil-related ES	Mechanisms	Justification
Carbon sequestration	Land cover and soil amendments change the carbon balance in the soil and, therefore, the soil's capacity to sequester and store carbon.	Soil is the Earth's largest carbon reservoir. Soil carbon supports other ES, such as food production, nutrient cycling, and the conservation of soil biodiversity (Hoffland *et al.*, 2020; Santos *et al.*, 2021).
Carbon cycling	Supporting function for climate regulation and fertility	The carbon cycle regulates climate by controlling atmospheric CO_2 levels and supports soil fertility by recycling essential nutrients for

		ecosystems (Oliveira *et al.*, 2016, 2017)
Soil fertility provision	Soil is a source of essential chemical elements (nutrients) that support ecological functions. Land use changes can increase or deplete the supply of these nutrients to plants and soil biota.	Soil fertility is essential for plant growth and biological processes (Eichert and Fernández, 2023).
Soil structure and water regulation	Soil structure regulates the global hydrological and gaseous cycles. Land use changes affect water and air regulation (drainage, retention, and availability), and soil protection against erosion and soil loss.	The structure of the soil is made up of pores of different sizes, shapes, and functionalities, responsible for drainage, storage, and the supply of water and oxygen to plants (Rabot *et al.*, 2018).

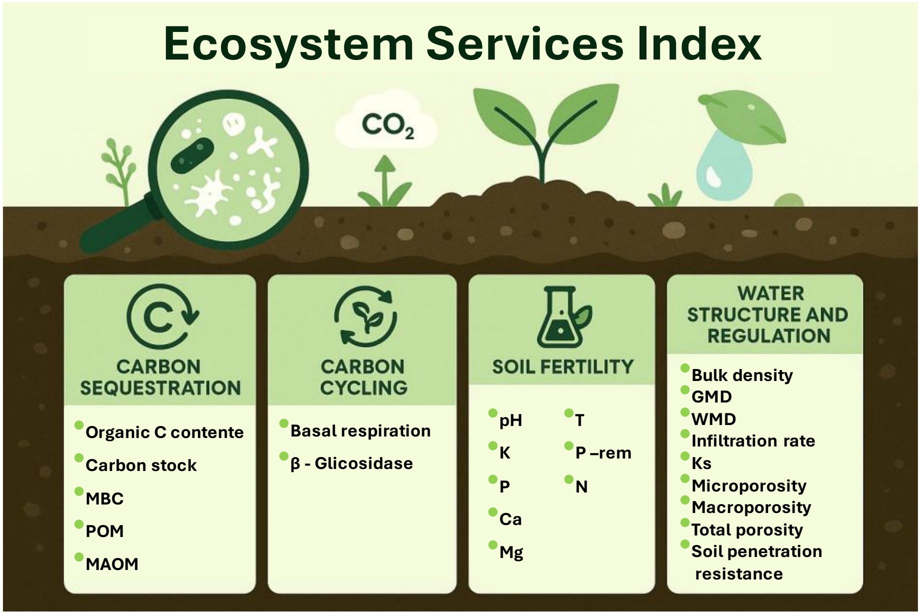


Fig. 3. List of indicators used in each ecosystem service. MBC = microbial biomass carbon; POM = particulate organic matter; MAOM = organic matter associated with the mineral fraction; K = potassium; P = phosphorus; Ca = calcium; Mg = magnesium; T = cation exchange capacity at pH 7.0; P-rem = remaining phosphorus; N = nitrogen; GMD = geometric mean diameter; WMD = weighted mean diameter; Ks = saturated conductivity.

To calculate the ecosystem service indices, the soil data (i.e., the physical and biochemical indicators) were normalized into an ordinal score ranging from 0 to 1 by using the linear scoring functions. For doing that, the indicators were ranked in ascending or descending order, depending on whether the indicators follow the logic “more is better for ES delivery” or “less is better for ES delivery”. For the “more is better” indicators (i.e., SOC, GMD, and WMD), each observation was divided by the highest observed value, which was assigned a value of 1.0 by definition. As to the “less is better” parameters (i.e., RP and Bd), the lowest observed value was assigned a value of 1.0. This value was then divided by the other observations to obtain their relative scores. In this way, all the indicators from all the services follow the same rule, where 1 is the best value and 0 is the worst.

Subsequently, we integrated the related indicator scores to create each soil ecosystem services sub-index (Silva-Olaya et al., 2021) through different approaches. For ES1, ES3, and ES4, which are represented by 5, 8, and 9 indicators, respectively, the weighting of the indicators was based on principal component analysis (PCA). Basically, the PCA loads for each indicator were multiplied by the corresponding normalized values (previous step) and added together, thus generating a single value for each principal component statistically relevant (i.e., eigenvalue > 1; Kaiser criterion). This value was then multiplied by the proportion of the total variance explained by the principal component. Finally, the values of all the PCs were added together to make up the ES sub-index (Silva-Olaya et al., 2022) (Eq. 1).

$$ES_{si} = \sum_{k=1}^{n} \alpha \text{ x } (Is \text{ x } Iw) \quad \text{(Eq. 1)}$$

Where ES_{si} is the ecosystem services sub-index, α is the total variance explained by the principal component (eigenvalues), *Is* is the indicator's score (normalized value), and *Iw* is the indicator's weight based on its eigenvector within each principal component. For the ES2 calculation, which is made up of only two indicators, the weight of each indicator was considered equal (50%).

Finally, we calculated the overall SES index for each land use system at each soil class. As seen in Table 2, all the soil-related ES are equally important in the soil-water-plant context; therefore, a simple additive approach was applied to integrate the sub-indexes into the general index. Through this approach, an average was carried out, where the individual sub-indexes of the soil-related ES were added together, and then the product was divided by the number of ecosystem services. This procedure was performed for all land use combinations and soil classes evaluated. To represent an overall ES index for each soil class, an average of the ES indices of the land use within each soil class was made.

2.4 Data analysis

To understand the influence of land uses on the soil's capacity to provide ecosystem services (ES), the dataset was tested for homogeneity of variances and normality using Bartlett's test (p > 0.05). Next, the individual ES sub-indices (carbon sequestration, carbon cycle, soil fertility and soil structure, and water regulation) were compared between land uses using one-way analysis of variance (ANOVA). To identify the presence of statistically significant differences between the land use systems for each soil class, Tukey's test was performed ($p < 0.05$).

Principal Component Analysis (PCA) was also used to determine the weight of each indicator in the ES1, ES3, and ES4 sub-indices, and to calculate the weighted contribution of each indicator to the composition of the sub-index (Kaiser's criterion), thereby exploring the synergies and trade-offs between the ecosystem services evaluated.

To further understand the relationships between the ecosystem services sub-indices, Canonical Correlation Analysis (CCA) was used. This multivariate statistical methodology evaluates the interdependence between two sets of variables - in this case, groups of indicators from each SE - and identifies the degree to which linear combinations of one group are correlated with combinations of the other. The strength and significance of the canonical correlations were evaluated using Student's t-test ($p < 0.05$). All statistical analyses were performed using the R software version 4.4.2 (R Core Team, 2023) in the RStudio environment (version 2024.09.1+394).

3 Results and discussion

3.1 Influence of land use on the soil’s ability to provide ecosystem services

3.1.1 Ecosystem service 1 – Carbon sequestration

In general, there were no statistical differences between soils for the same uses (Fig. S1), when evaluated individually, indicating that Ultisols and Latosols can behave in the same way when subjected to the same management systems (Totti et al., 2025). The highest value presented for ES1 was in the use of pasture (0.85) and forest fragment (0.84), however, there were no statistical differences between these uses and forest restoration (0.75) and sugarcane (0.74), as shown in Fig. 4. This result is confirmed by the fact that grasses, such as sugarcane, are characterized by high root system renewal (Oliveira et al., 2022). This results in higher carbon input into the soil, resulting in a higher carbon stock in the soil, on par with forest fragments and forest restoration (Rousset et al., 2024).

Annual crops (0.69) tend to have shallower and less developed roots, which reduces the ability to sequester carbon in the soil (Jansson et al., 2021); for this reason, it had a lower index value than the others. Finally, cassava had the lowest result (0.48). A study conducted by Seena et al. (2022) highlighted that cassava cultivation can negatively impact carbon sequestration because of its contribution to the rapid decomposition of organic matter. This happens because management practices, such as soil disturbance and low vegetation cover, increase the release of CO_2.

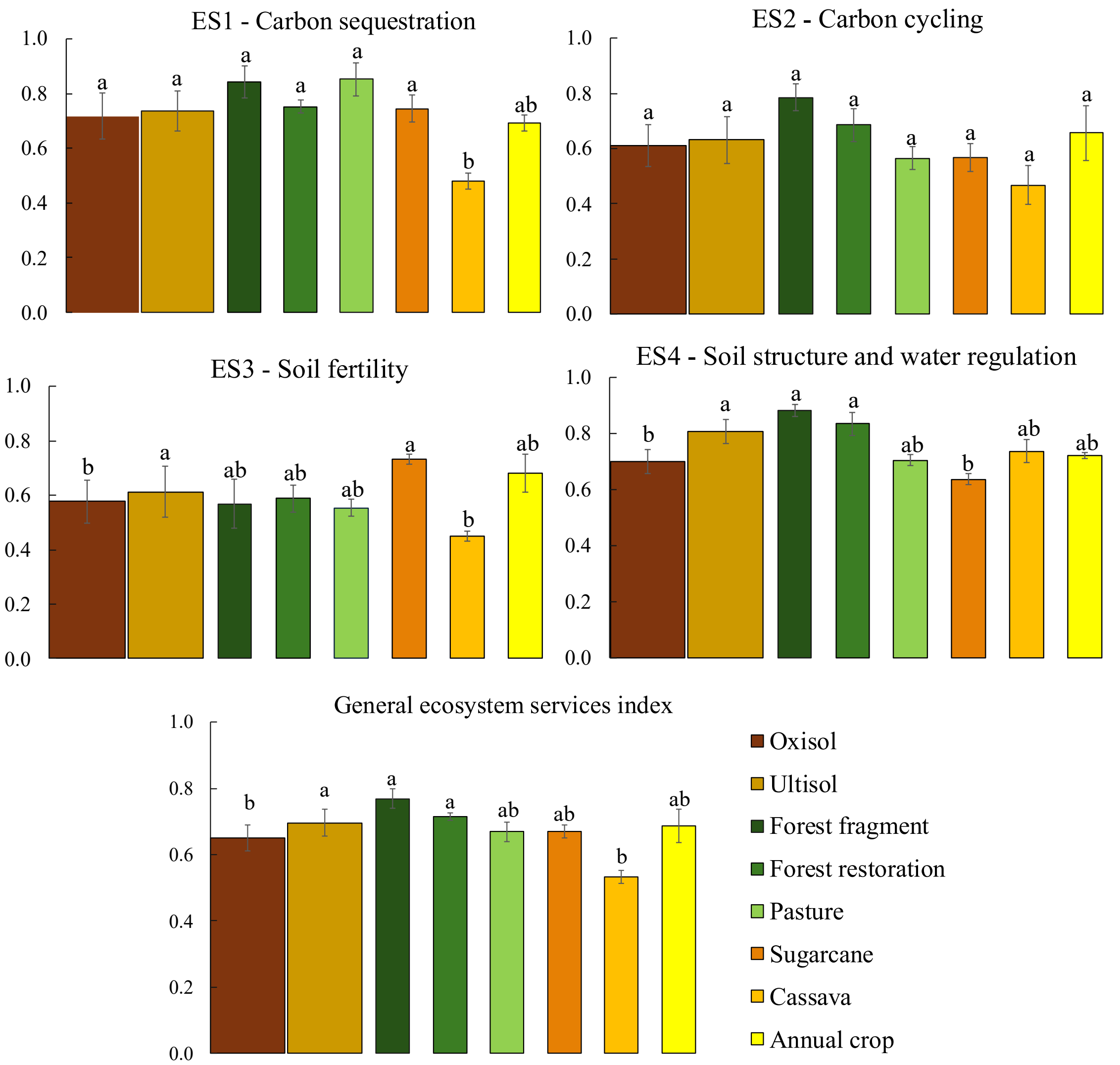


Fig. 4. Index ecosystem services provided by the soils in the Pontal do Paranapanema region - Atlantic Forest, SP, Brazil.

3.1.2 Ecosystem service 2 – Carbon cycling

In general, for ES2 (Fig. 4), due to the great variability of the data between replicates (Fig S2), there were no statistical differences between the land uses. For ES2 (Fig. 4), the highest value of the index was presented by the forest fragment, with 0.79. The diversity of species used in this land use plays a key role, ensuring that soils with different textures can accumulate carbon (Mantovani et al., 2023). The following are the values presented by forest restoration (0.69), annual crop (0.66), pasture (0.57), and sugarcane (0.57). Litter and root biomass are essential to overcome texture variations and favor carbon sequestration in restoration areas (Paula et al., 2022), just as root renewal favors this process in use with grasses (Oliveira et al., 2022). Once again, the use of cassava had the lowest value, with an ES for nutrient cycling of only 0.47. Despite this, there were no statistical differences between the SE 2 indices of land uses.

The high values of ES2, as occurred in the forest fragment, may be indicative of high carbon and nutrient cycling in the soil. According to Carvalho et al. (2010), in tropical forests, high humidity and temperature accelerate the decomposition of soil organic matter, resulting in rapid cycling of carbon and nutrients, limiting their accumulation in the soil.

3.1.3 Ecosystem service 3 – Soil fertility

In general, for ES3 (Fig. 4), despite the great variability of the data between the replications, sugarcane (0.73) presented the highest values (Table S2). This is mainly because they are crops, where there is constant fertilization of the soil in these cropping systems. When it comes to sugarcane, in addition to traditional fertilization, the system receives vinasse and produces a good amount of straw from sugarcane production (Kumar et al., 2024).

The annual tillage system (0.68) also receives frequent fertilization; however, the rapid decomposition of organic matter and nutrient cycling in this type of crop makes this land use not statistically different from the forest fragment (0.57), forest restoration (0.59), and pasture (0.55) uses. The cultivation of cassava, although it receives soil fertilization, can be applied in smaller quantities than recommended, because in the region, it is used as a subsistence crop by producers with less financial power. In addition, the system offers a favorable environment for cycling and leaching, and export of nutrients from the soil (Seena et al., 2022). Although all uses did not present statistically significant differences, soil uses without frequent soil fertilization showed lower ES3 values, indicating that they were less fertile.

3.1.4 Ecosystem service 4 – Soil structure and water regulation

As expected, the forest fragment presented the highest value of ES4, with a value of 0.88. As there is no traffic or roundabout in this land use, a stable environment is created, alleviating the indicators of this SE (Agbeshie et al., 2022). The same stable environment is being established in forest restoration (Gardon et al., 2020), which is why this land use showed the highest value (0.83). The other land uses, with lower rates, are under frequent traffic, whether of cattle, in the case of pastures, or of agricultural machinery for cultivated soils. For the same soil and moisture conditions, the heavier the machinery traditionally used, the greater the soil compaction (Hákansson and Voorhees, 1997), leading to a lower ES4, resulting in the order of land use: cassava (0.74), annual crop (0.72), pasture (0.70), and sugarcane (0.64).

This was the only SE where cassava did not present the lowest index, probably because of its management. Despite the traffic of machinery, extensive soil disturbance during harvesting operations can contribute to the reduction of Bd and consequently increase soil macropores, water infiltration, and conductivity in the soil (Figueiredo et al., 2017), resulting in ES4 as the most conservationist conditions.

For the sugarcane crop, which presented the lowest ES4 value, the harvesting operations include the use of heavy machinery, both harvesters and transport trucks, which can contribute to a greater degradation of the soil structure (Esteban et al., 2019). This heavy machinery traffic can result in soil compaction, which can compromise its porosity and drainage capacity. Thus, it is essential to adopt appropriate management practices in these areas to minimize soil compaction and avoid possible productivity losses (Oliveira et al., 2022).

This ES showed a statistical difference between the soil classes. Ultisol presented the best result, with a value of 0.80, while Oxisol presented a value of 0.70. The dystrophic Red Oxisol is characterized by being a homogeneous and well-structured soil (Bócoli et al., 2021). However, as this region has predominantly sandstones, the soils usually have lighter textures (Marconato et al., 2006). These soils may contain a greater amount of macropores, which may provide a greater percolation of water through the soil profile (Table S3). On the other hand, Ultisol may have a higher amount of clay at depth due to its formation process. This greater amount of clay can characterize a denser structure, which in soils with low clay content can be beneficial, helping in the formation of micropores and promoting water retention in these soils (Santos et al., 2018). These differences from the point of view of soil genesis may have been essential for the analysis of these soils, showing that the structure, behavior, and water retention are different and should be considered in the management of these soils.

3.1.5 General ecosystem services index

The general index of ecosystem services presented three distinct statistical groups, refuting the hypothesis of this study that land use can offer the same SE at the same intensity in different soils (Fig. 4). In the general index of ecosystem services, forest restoration is statistically equal to the system of forest fragments, indicating its effectiveness in recovering soil functionality. This aligns with the results achieved by Christin et al. (2016), who concluded that by choosing the right strategy, forest restoration can recover much of the SE lost due to degradation.

The uses sugarcane (0.67), annual crop (0.69), and pasture (0.67) were statistically equal, indicating that these land uses can be a sustainable use option for this region, when management is well planned (Kumar et al., 2024). However, special attention should be paid to the use of sugarcane to ES4, as discussed earlier.

The cassava crop presented the worst performance in the general HE indexes, with a value of 0.53. This result reflects the negative impact of intensive management, such as frequent soil disturbance and low soil cover, which strongly affects carbon sequestration and nutrient cycling. This land use, under the current management system, was not sustainable for this region, requiring special care for soil conservation (Seena et al., 2022).

To improve the sustainability of cassava cultivation and increase the provision of soil ecosystem services, it is essential to implement conservation practices that reduce physical and chemical soil degradation. The use of no-till or minimum tillage, combined with the planting of cover crops, such as green manure or mulch, helps to improve soil structure, with greater accumulation of organic matter and reduced erosion (Turetta et al., 2017; Oliveira et al., 2022). In addition, crop rotation with legumes benefits the supply of and stimulates soil biological activity (Bhunia et al., 2021).

3.2 Principal Component Analysis (PCA) for Soil-Related ES Sub-indices Evaluated

The data presented in Fig. 5 shows the relationship between soil-related ES sub-indices and land uses, investigated through PCA. The first two components explained 61.4% of the variance in Ultisol and 82.1% in Oxisol. It is possible to notice that, in Ultisol, there is a clear relationship between the forest fragment and ES4, as this land use provides a stable environment, with good soil structure and aeration (Agbeshie et al., 2022). The forest restoration showed a relationship with ES3, indicating soil fertility recovery (Mosier et al., 2021), and, still in the Ultisol, there was also an inverse correlation between cassava and ES4, once again proving that this land use harms soil sustainability (Seena et al., 2022).

In the Oxisol, the main correlations were between the forest fragment and ES4 and ES2, supporting Zinn et al. (2002), who concluded that when soil structure is highly aerated, it can contribute to rapid carbon cycling. Finally, pasture use showed a correlation with ES1 and ES2, confirming the previously discussed results, revealing that pasture has a strong relations with carbon storage and cycling in the soil (Silva-Olaya et al., 2022).

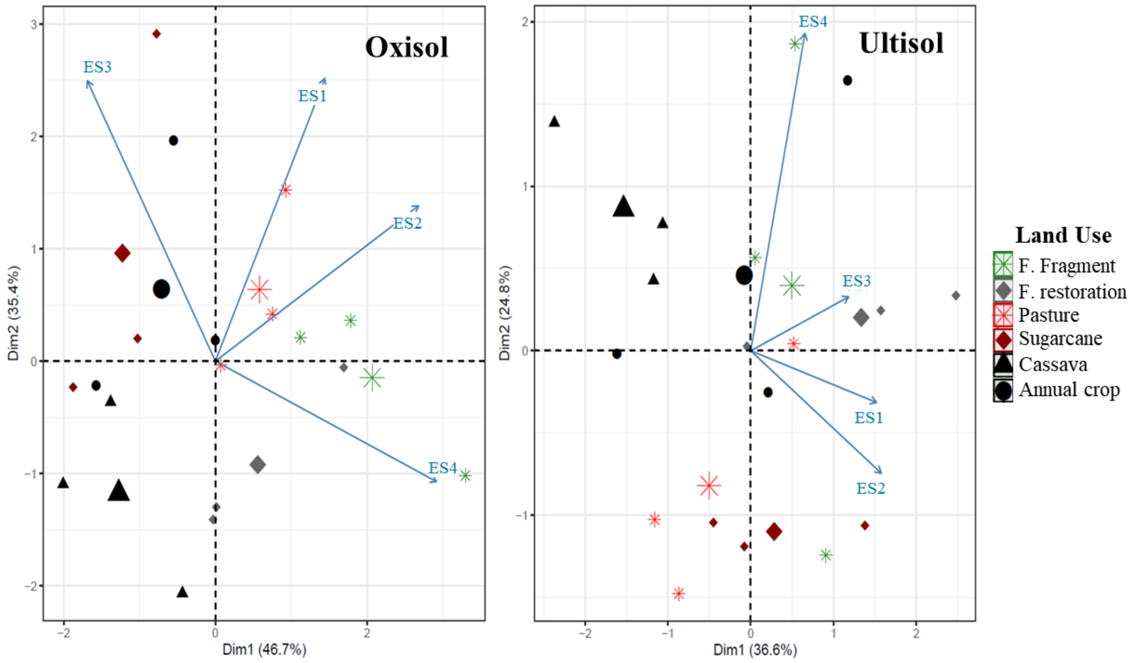


Fig. 5. Principal component analysis (PCA) of the four evaluated soil-related sub-indices under the forest fragment, forest restoration, pasture, sugarcane, cassava, and annual crop. Note: Carbon stock (ES1), C cycling (ES2), soil fertility (ES3), and water regulation (ES4).

3.3 Interactions between ecosystem services

Canonical correlation analysis (CCA) revealed correlations between the soil properties indices and soil-related ES (Fig. 6). The CCA makes it possible to present and quantitatively express the complex interrelationships between the large groups of ES indicators (Oliveira et al., 2019). In Ultisol, the main correlations were between the soil structure and water regulation (ES4) and the carbon sequestration (ES1), carbon cycling (ES2), and soil fertility (ES3). The soil structure is closely linked to the water and nutrient retention capacity, which directly affects fertility (Mosier et al., 2021). Soil structure also has a major impact on the carbon stock, especially regarding the carbon cycling and storage in the soil (Zinn et al., 2007, 2005).

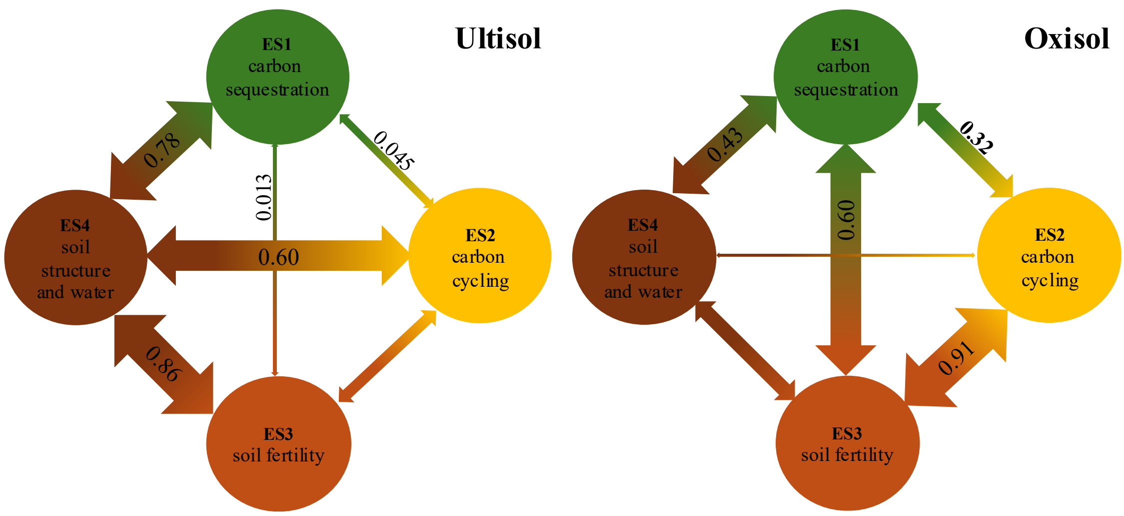


Fig. 6. Schematic representation of the canonical correlations between the sub-indices of soil-related ecosystem services evaluated in typical soils of the Atlantic Forest.

Correlations in Oxisol behaved somewhat differently. The highest correlation (0.91) was between soil fertility and carbon cycling. Soil fertility is related to carbon cycling because the reduction of the soil carbon stocks also decreases nutrient retention and availability to plants, thus reducing soil fertility (Mantovani et al., 2024; Silva-Olaya et al., 2022). Fertility is also related to carbon sequestration. Most of the C in the soil exists as organic carbon (SOC), the main component of the soil organic matter that, in tropical soils, such as Oxisol, is fundamental to soil fertility and health (Bócoli et al., 2021).

Finally, soil structure and water regulation (ES4) were related to carbon sequestration (ES1). Soil management practices directly influence the provision of these soil functions (Tesfaye et al., 2022). These practices can increase soil carbon content to sufficient levels to support soil structure, nutrient cycling, and primary food production (Zhao et al., 2022).

Although the results provide a comprehensive analysis of the ecosystem services, the absence of socioeconomic data, soil losses due to erosion, and information on plant growth represents a limitation of the work for a broader analysis. Future studies could integrate these and other ecosystem services for a more complete understanding of the ecosystem services that the region can offer.

3.4 Trade-offs and synergies between soil properties indices

PCA was applied for each land use, considering both soils, to identify synergies and trade-offs between sub-indices (Fig. 7). In summary, there was synergy in all land uses and soils, and trade-offs only in pasture and cassava for both soils, and forest fragments only for Oxisol. The main synergies indicated by PCA were between carbon cycling (ES2) and soil fertility (ES3) for sugarcane and cassava in both soils, and pasture and annual crop for Oxisol. The same interaction between these ES was reported by Zhao et al. (2022), who evaluated ES in predominant Chinese soils under different land use types. The carbon cycle influences soil fertility, mainly in more clayey soils, since clay aids in aggregation and thus provides greater protection for the organic matter. This, in turn, contributes to a greater generation of electric charges in the soil, improving its capacity to retain and supply nutrients in the soil (Bhunia et al., 2021).

Another synergy very present in the uses was between the ES2 – carbon cycling and ES4 – soil structure and water regulation. The soil carbon performs a fundamental biological function in dynamic regulation, flow, shapes, and soil nutrient cycling (Haghverdi and Kooch, 2019), and simultaneously aids soil aggregation, improves its structure, and increases the prevention of erosion (Mantovani et al., 2024).

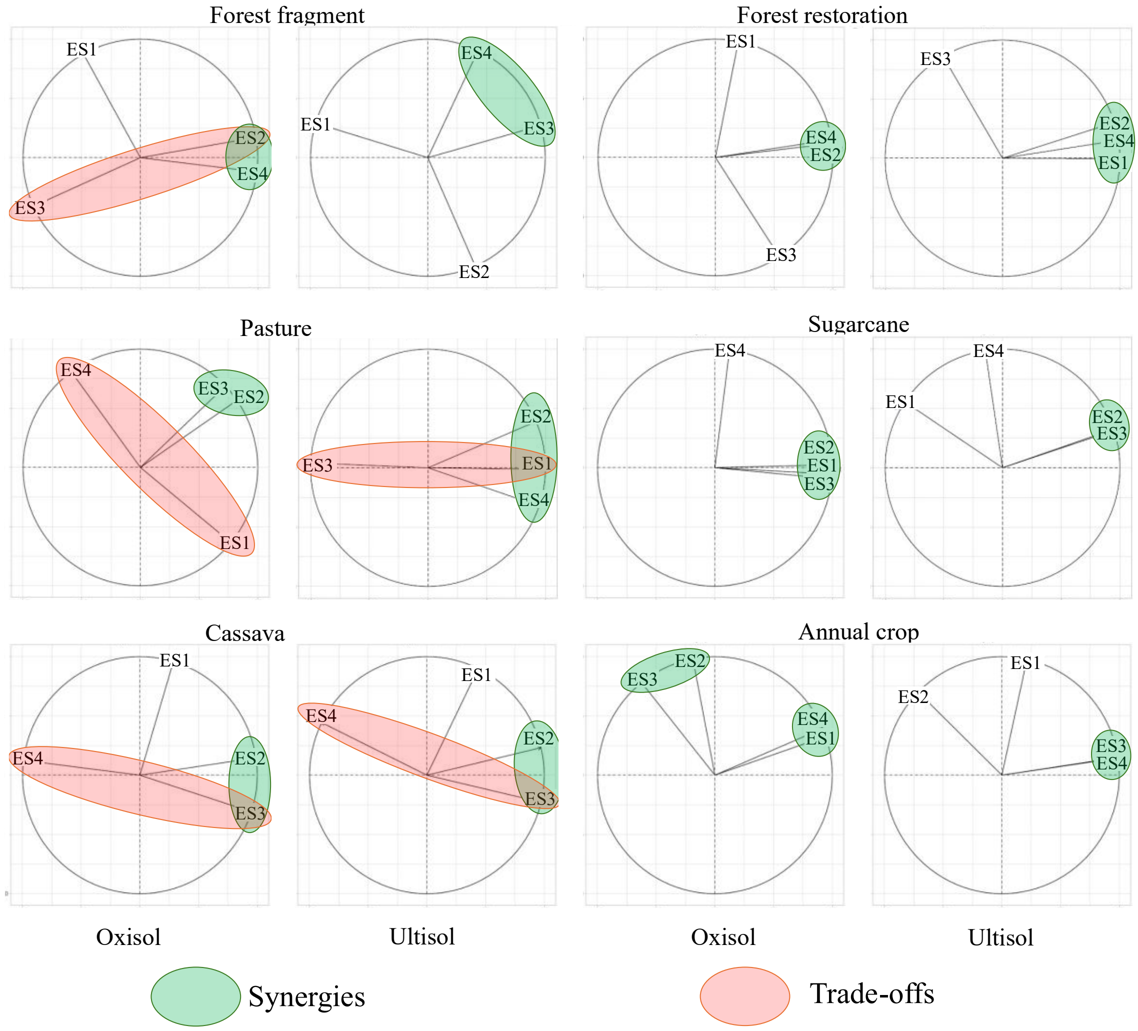


Fig. 7. Synergies and trade-offs between the sub-indices of the soil-related ecosystem services in forest fragments, forest restoration, pasture, sugarcane, cassava, and annual crop areas, in Oxisols and Ultisols. Note: Carbon stock (ES1), C cycling (ES2), soil fertility (ES3), and soil structure and water regulation (ES4).

Regarding trade-off, it was present in pasture use, between ES1 and ES3 in Ultisol and ES1 and ES4 in Oxisol. The PCA pointed out that, in this use, carbon stock can be impaired by low soil fertility as much as structure, which favors decomposition and carbon cycling (Zinn et al., 2005). In cassava, the trade-off was between ES3 and ES4 in both soils, indicating that the intensive soil tillage in this crop disadvantages soil fertility (Figueiredo et al., 2021; Seena et al., 2022).

Finally, in the forest fragment, the synergy between ES2 and ES3 indicated that high carbon cycling, as previously shown, is negatively influencing soil fertility. A study carried out by Baldotto and Xavier (2014) analyzed the relationship between the mineralization of organic matter and fertility in different classes of tropical soil. The study pointed out that in highly weathered, nutrient-poor soils, and with low CEC, as is the case with the Oxisols and Ultisols in this study, there are lower accumulations of carbon and low availability of negative charges, which impairs humification and, consequently, soil fertility.

4 Conclusions

This study confirmed that different land uses significantly influence the capacity of soil to provide ecosystem services in the Atlantic Forest biome. Thus, the hypothesis that conservation uses provide the same SE with the same intensity in different soil classes was refuted, since there were differences between soils for soil fertility, soil structure, water retention SE, and the overall ecosystem services index. Forest fragment land uses and forest restoration demonstrated greater carbon sequestration capacity, highlighting the importance of evergreen vegetation, soil cover, and high root renewal for environmental sustainability. On the other hand, cassava cultivation had the lowest rates in both soils, due to the negative impact of intensive soil management and tillage on soil fertility, structure, and carbon cycling.

In addition, the results indicated important synergies between SEs related to carbon cycling and soil fertility, and trade-offs in intensive systems, such as pasture and cassava. These findings reinforce the need for management practices adapted to the edaphic properties of each soil to promote the sustainability of land use. Finally, the SE indexes applied in this study offers a practical tool to assist in management and land use decisions in tropical regions of the Atlantic Forest biome, since it indicates which soil ecosystem services are impaired or enhanced in each management system, facilitating decision-making aimed at improving the production system.

Acknowledgments

We acknowledge the financial support of China Three Gorges Corporation (CTG-Brazil), Coordination of Improvement of Higher Education Personnel (CAPES), National Council for Scientific and Technological Development (CNPq) process 406903/2022-0, Foundation for Research Support of the State of Minas Gerais (FAPEMIG) process APQ-01173-24, and Institute for Ecological Research (IPÊ). SHGS, BMS, FAB and JCA thank CNPq or grants number 307532/2022-4, 311743/2021-8, 174948/2023-9, and 307059/2022-7, respectively.

5 REFERENCES

Adhikari, K., Hartemink, A.E., 2016. Linking soils to ecosystem services - A global review. Geoderma. https://doi.org/10.1016/j.geoderma.2015.08.009.

Agbeshie, A.A., Abugre, S., Atta-Darkwa, T., Awuah, R., 2022. A review of the effects of forest fire on soil properties. J For Res (Harbin). https://doi.org/10.1007/s11676-022-01475-4.

Anderson, T.-H., Domsch, K.H., 1993. The metabolic quotient for co, (QCO2) as a specific activity parameter to assess the effects of environmental conditions, such as pH, on the microbial biomass of forest soils, Soil Biol. Biochem.

Bhunia, S., Bhowmik, A., Mallick, R., Mukherjee, J., 2021. Agronomic efficiency of animal-derived organic fertilizers and their effects on biology and fertility of soil: A review. Agronomy. https://doi.org/10.3390/agronomy11050823.

Blake, G. R.; Hartge, K. H. Bulk density. *Em*: Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods. [s.l.] wiley, 1986. p. 363–375.

Bócoli, F.A., Dos Santos, W.J.R., Silva, S.H.G., Teixeira, A.F.D.S., Mancini, M., Curi, N., 2021. Study of an abnormal occurrence of oxisols in strongly undulated relief in the south of Minas Gerais, brazil, with support of pxrf and geomorphology. Ciencia e Agrotecnologia 45. https://doi.org/10.1590/1413-7054202145018121.

Carvalho, L.N., Avanzi, J., Cesar J., Naves, L.S.M., Mello, R.C., Cerri, E.P.C., 2010. Potencial de sequestro de carbono em diferentes biomas do Brasil 277 potencial de sequestro de carbono em diferentes biomas do brasil (1) revisão de literatura.

Christin, Z.L., Bagstad, K.J., Verdone, M.A., 2016. A decision framework for identifying models to estimate forest ecosystem services gains from restoration. For Ecosyst 3. https://doi.org/10.1186/s40663-016-0062-y.

Dick, R.P., Breakwell, D.P., Turco, R.F., 2015. Soil enzyme activities and biodiversity measurements as integrative microbiological indicators, in: Methods for Assessing Soil Quality. wiley, pp. 247–271. https://doi.org/10.2136/sssaspecpub49.c15.

Eichert, T., Ferná Ndez, V., 2023. Uptake and release of elements by leaves and other aerial plant parts $. https://doi.org/10.1016/B978-0-12-384905.

Figueiredo, P.G., Bicudo, S.J., Chen, S., Fernandes, A.M., Tanamati, F.Y., Djabou-Fondjo, A.S.M., 2017. Effects of tillage options on soil physical properties and cassava-dry-matter partitioning. Field Crops Res 204, 191–198. https://doi.org/10.1016/j.fcr.2016.11.012.

Esteban, D. A. A., de Souza, Z. M., Tormena, C. A., Lovera, L. H., de Souza Lima, E., de Oliveira, I. N., & de Paula Ribeiro, N., 2019. Soil compaction, root system and productivity of sugarcane under different row spacing and controlled traffic at harvest. Soil and Tillage Research, 187(June 2018), 60–71. https://doi.org/10.1016/j.still.2018.11.015.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Stuart Chapin, F., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Colin Prentice, I., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use 370–374.

Gardon, F.R., Santos, R.F. dos, Rodrigues, R.R., 2020. Brazil's forest restoration, biomass and carbon stocks: A critical review of the knowledge gaps. For Ecol Manage 462, 117972. https://doi.org/10.1016/j.foreco.2020.117972.

Haghverdi, K., Kooch, Y., 2019. Effects of diversity of tree species on nutrient cycling and soil-related processes. Catena (Amst) 178, 335–344. https://doi.org/10.1016/j.catena.2019.03.041.
Hákansson, I., Voorhees, W.B., 1997. Soil Compaction. CRC Press.

Hoffland, E., Kuyper, T.W., Comans, R.N.J., Creamer, R.E., 2020. Eco-functionality of organic matter in soils. Plant Soil. https://doi.org/10.1007/s11104-020-04651-9.

Hyun, J., Kim, Y.J., Kim, A., Plante, A.F., Yoo, G., 2022. Ecosystem services-based soil quality index tailored to the metropolitan environment for soil assessment and management. Science of the Total Environment 820. https://doi.org/10.1016/j.scitotenv.2022.153301.

Intergovernmental Panel on Climate Change (IPCC), 2023. Future Global Climate: Scenario-based Projections and Near-term Information, in: Climate Change 2021 – The Physical Science Basis. Cambridge University Press, pp. 553–672. https://doi.org/10.1017/9781009157896.006.

Jansson, C., Faiola, C., Wingler, A., Zhu, X.G., Kravchenko, A., de Graaff, M.A., Ogden, A.J., Handakumbura, P.P., Werner, C., Beckles, D.M., 2021. Crops for Carbon Farming. Front Plant Sci 12. https://doi.org/10.3389/fpls.2021.636709.

Jónsson, J.Ö.G., Davíðsdóttir, B., Nikolaidis, N.P., 2017. Valuation of Soil Ecosystem Services. pp. 353–384. https://doi.org/10.1016/bs.agron.2016.10.011.

Kemper, W.D., Chepil, W.S., 1965. Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, 9th ed. Madison. https://doi.org/https://doi.org/10.2134/agronmonogr9.1.c39.

Klute, A., Dirksen, C., 2018. Hydraulic conductivity and diffusivity: Laboratory methods, in: Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods. wiley, pp. 687–734. https://doi.org/10.2136/sssabookser5.1.2ed.c28.

Kumar, A., Meena, S.K., Singh, S.K., Sinha, S.K., Singh, A.K., 2024. Carbon Sequestration in Sugarcane Plant-soil System as Influenced by Nutrient Integration Practices under Indo-Gangetic Plains of India. J Adv Biol Biotechnol 27, 116–125. https://doi.org/10.9734/jabb/2024/v27i5769.

Latawiec, A. E., Strassburg, B. B. N., Silva, D., Alves-Pinto, H. N., Feltran-Barbieri, R., Castro, A., Iribarrem, A., Rangel, M. C., Kalif, K. A. B., Gardner, T., & Beduschi, F. 2017. Improving land management in Brazil: A perspective from producers. Agriculture, Ecosystems and Environment, 240, 276–286. https://doi.org/10.1016/j.agee.2017.01.043.

Leuthold, S.J., Haddix, M.L., Lavallee, J., Cotrufo, M.F., 2023. Physical fractionation techniques, in: Encyclopedia of Soils in the Environment. Elsevier, pp. 68–80. https://doi.org/10.1016/b978-0-12-822974-3.00067-7.

Mantovani, V. A., Terra, M. D. C. N. S., Rodrigues, A. F., Silva, C. A., Guo, L., de Mello, J. M., & de Mello, C. R., 2024. Unprecedentedly high soil carbon stocks and their spatial variability in a seasonally dry Atlantic Forest in Brazil. *Catena*, *235*, 107696. https://doi.org/10.1016/j.catena.2023.107696.

Mantovani, V.A., Terra, M. de C.N.S., Rodrigues, A.F., Cordeiro, N.G., de Mello, J.M., de Mello, C.R., 2023. Biotic and abiotic drivers of stemflow carbon enrichment ratio in tropical trees. Trees - Structure and Function 37, 467–483. https://doi.org/10.1007/s00468-022-02363-4.

Mantovani, V.A., Terra, M. de C.N.S., Rodrigues, A.F., Silva, C.A., Guo, L., de Mello, J.M., de Mello, C.R., 2024. Unprecedentedly high soil carbon stocks and their spatial variability in a seasonally dry Atlantic Forest in Brazil. Catena (Amst) 235. https://doi.org/10.1016/j.catena.2023.107696.

Marconato, A., Turra, B. B., Salvador, E. D., Chieregati, L. A., D'Agostino, L. Z., Perrotta, M. M., & Lopes, R. C., 2006. Mapa Geológico do estado de São Paulo. https://doi.org/https://rigeo.sgb.gov.br/handle/doc/2966.

Mendes, L.M., César, R.G., Uezu, A., Beltrame, T.P., Rodriguez, L.C.E., Gomes, H.B., Cullen, L., 2021. Large canopy and animal-dispersed species facilitate natural regeneration in tropical forest restoration. Restor Ecol 29. https://doi.org/10.1111/rec.13406.

Mendonça, E.S. and Matos, E.S. (2005). Matéria orgânica do solo: métodos de análises. Viçosa, MG: Editora UFV.

Mosier, S., Córdova, S.C., Robertson, G.P., 2021. Restoring Soil Fertility on Degraded Lands to Meet Food, Fuel, and Climate Security Needs via Perennialization. Front Sustain Food Syst. https://doi.org/10.3389/fsufs.2021.706142.

Oliveira, D.M. da S., Paustian, K., Cotrufo, M.F., Fiallos, A.R., Cerqueira, A.G., Cerri, C.E.P., 2017. Assessing labile organic carbon in soils undergoing land use change in Brazil: A comparison of approaches. Ecol Indic 72, 411–419. https://doi.org/10.1016/j.ecolind.2016.08.041.

Oliveira, D.M. da S., Paustian, K., Davies, C.A., Cherubin, M.R., Franco, A.L.C., Cerri, C.C., Cerri, C.E.P., 2016. Soil carbon changes in areas undergoing expansion of sugarcane into pastures in south-central Brazil. Agric Ecosyst Environ 228, 38–48. https://doi.org/10.1016/j.agee.2016.05.005.

Oliveira, D.M.S., Cherubin, M.R., Franco, A.L.C., Santos, A.S., Gelain, J.G., Dias, N.M.S., Diniz, T.R., Almeida, A.N., Feigl, B.J., Davies, C.A., Paustian, K., Karlen, D.L., Smith, P., Cerri, C.C., Cerri, C.E.P., 2019. Is the expansion of sugarcane over pasturelands a sustainable strategy for Brazil's bioenergy industry? Renewable and Sustainable Energy Reviews 102, 346–355. https://doi.org/10.1016/j.rser.2018.12.012.

Oliveira, I.N. de, Souza, Z.M. de, Bolonhezi, D., Totti, M.C.V., Moraes, M.T. de, Lovera, L.H., Lima, E. de S., Esteban, D.A.A., Oliveira, C.F., 2022. Tillage systems impact on soil physical attributes, sugarcane yield and root system propagated by pre-sprouted seedlings. Soil Tillage Res 223. https://doi.org/10.1016/j.still.2022.105460.

Paula, R.R., Calmon, M., Lopes-Assad, M.L., Mendonça, E. de S., 2022. Soil organic carbon storage in forest restoration models and environmental conditions. J For Res (Harbin). https://doi.org/10.1007/s11676-021-01426-5.

R Core Team. (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.r-project.org/.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.J., 2018. Soil structure as an indicator of soil functions: A review. Geoderma. https://doi.org/10.1016/j.geoderma.2017.11.009.

Rousset, C., Segura, C., Gilgen, A., Alfaro, M., Mendes, L.A., Dodd, M., Dashpurev, B., Bastidas, M., Rivera, J., Merbold, L., Vázquez, E., 2024. What evidence exists relating the impact of different grassland management practices to soil carbon in livestock systems? A systematic map protocol. Environ Evid 13. https://doi.org/10.1186/s13750-024-00345-2.

RStudio Team. (2023). RStudio: Integrated Development Environment for R. RStudio, PBC. Recuperado de https://www.rstudio.com/.

Santos, R.S., Wiesmeier, M., Cherubin, M.R., Oliveira, D.M.S., Locatelli, J.L., Holzschuh, M., Cerri, C.E.P., 2021. Consequences of land-use change in Brazil's new agricultural frontier: A soil physical health assessment. Geoderma 400. https://doi.org/10.1016/j.geoderma.2021.115149.

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C.; Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araujo Filho, J. C., Oliveira, J. B., & Cunha, T. J. F., 2018. Sistema brasileiro de classificação de solos. Em Embrapa Solos (5o ed).

Seena Radhakrishnan, A.R., Suja, G., Sreekumar, J., 2022. How sustainable is organic management in cassava? Evidences from yield, soil quality, energetics and economics in the humid tropics of South India. Sci Hortic 293, 110723. https://doi.org/10.1016/j.scienta.2021.110723.

Silva, A.J.P., Lopes, R.C., Vasconcelos, A.M., Bahia, R.B.C., 2003. Bacias Sedimentares Paleozóicas e Meso Cenozóicas Interiores In: Bizzi, L.A., Schobbenhaus, C., Vidotti, R.M., Gonçalves, J.H. Geologia, tectônica e recursos minerais do Brasil: texto, mapas SIG. Brasília: CPRM – Serviço Geológico do Brasil.

Silva-Olaya, A.M., Ortíz-Morea, F.A., España-Cetina, G.P., Olaya-Montes, A., Grados, D., Gasparatos, A., Cherubin, M.R., 2022. Composite index for soil-related ecosystem services assessment: Insights from rainforest-pasture transitions in the Colombian Amazon. Ecosyst Serv 57. https://doi.org/10.1016/j.ecoser.2022.101463.

Smith, P., Keesstra, S.D., Silver, W.L., Adhya, T.K., 2021. The role of soils in delivering Nature's Contributions to People. Philosophical Transactions of the Royal Society B: Biological Sciences 376. https://doi.org/10.1098/rstb.2020.0169.

Stolf, R., Murakami, J.H., Brugnaro, C., Silva, L.G., Silva, L.C.F. da, Margarido, L.A.C., 2014. Penetrômetro de impacto stolf - programa computacional de dados em EXCEL-VBA. Rev Bras Cienc Solo 38, 774–782. https://doi.org/10.1590/S0100-06832014000300009.

Teixeira, P.C. Donagemma, G.K., Fontana, A., Teixeira, W.G., 2017. Manual de métodos de análise de solos.

Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G., 2017. Manual de Métodos de Análise de Solo, 3rd ed, Manual de métodos de análise de solo. Brasília. DF.

Tesfaye, B., Lengoiboni, M., Zevenbergen, J., Simane, B., 2022. Land Preservation Uptakes in the Escarpments of North-eastern Ethiopia: Drivers, Sustainability, and Constraints. Land (Basel) 11. https://doi.org/10.3390/land11050676.

Totti, M.C.V., Zinn, Y.L., Silva, S.H.G., Silva, B.M., Bócoli, F.A., Faria, V.L. de, Montes, A.O., Acuña-Guzman, S.F., Uezu, A., Cullen Junior, L., Fernandes, V.F., Avanzi, J.C., 2025. Organic carbon stocks across various land use systems in Sandy Ultisols and Oxisols in Brazil. Geoderma Regional 40. https://doi.org/10.1016/j.geodrs.2025.e00924.

Turetta, A. P. D., Castro, S. S., Polidoro, J. C., 2017. Solos, sustentabilidade e provisão de serviços ecossistêmicos, in: BOLETIM INFORMATIVO DA SBCS. pp. 26–30.

Turetta, A.P.D., Castro, S.S., Polidoro, J.C., 2017. Solos, sustentabilidade e provisão de serviços ecossistêmicos, in: Boletim informativo da SBCS. pp. 26–30.

Zhang, R., 1997. Determination of Soil Sorptivity and Hydraulic Conductivity from the Disk Infiltrometer. Soil Science Society of America Journal 61, 1024–1030. https://doi.org/10.2136/sssaj1997.03615995006100040005x.

Zhao, R., Gabriel, J.L., Rodríguez Martín, J.A., Feng, Z., Wu, K., 2022. Understanding trade-offs and synergies among soil functions to support decision-making for sustainable cultivated land use. Front Environ Sci 10. https://doi.org/10.3389/fenvs.2022.1063907.

Zinn, Y.L., Lal, R., Bigham, J.M., Resck, D.V.S., 2007. Edaphic Controls on Soil Organic Carbon Retention in the Brazilian Cerrado: Texture and Mineralogy. Soil Science Society of America Journal 71, 1204–1214. https://doi.org/10.2136/sssaj2006.0014.

Zinn, Y.L., Lal, R., Resck, D.V.S., 2005. Changes in soil organic carbon stocks under agriculture in Brazil. Soil Tillage Res 84, 28–40. https://doi.org/10.1016/j.still.2004.08.007.

Zinn, Yuri.L., Resck, D.V.S., da Silva, J.E., 2002. Soil organic carbon as affected by afforestation with Eucalyptus and Pinus in the Cerrado region of Brazil. For Ecol Manage 166, 285–294. https://doi.org/10.1016/S0378-1127(01)00682-X.

6 Supplementary material

Table S 1. Land use history of sampling points in the study areas.

Locations	Soil	2015	2017	2019	2021	2023
1	Ultisol	Fragment				
2	Ultisol	Fragment				
3	Ultisol	Fragment				
4	Oxisol	Fragment				
5	Oxisol	Fragment				
6	Oxisol	Fragment				

<table>
<tr><td>7</td><td>Ultisol</td><td colspan="4">Restoration</td></tr>
<tr><td>8</td><td>Ultisol</td><td>Pasture</td><td colspan="3">Restoration</td></tr>
<tr><td>9</td><td>Ultisol</td><td colspan="4">Restoration</td></tr>
<tr><td>10</td><td>Oxisol</td><td>Pasture</td><td colspan="3">Restoration</td></tr>
<tr><td>11</td><td>Oxisol</td><td colspan="4">Restoration</td></tr>
<tr><td>12</td><td>Oxisol</td><td colspan="4">Restoration</td></tr>
<tr><td>13</td><td>Ultisol</td><td colspan="4">Pasture</td></tr>
<tr><td>14</td><td>Ultisol</td><td colspan="4">Pasture</td></tr>
<tr><td>15</td><td>Ultisol</td><td colspan="4">Pasture</td></tr>
<tr><td>16</td><td>Oxisol</td><td colspan="4">Pasture</td></tr>
<tr><td>17</td><td>Oxisol</td><td colspan="4">Pasture</td></tr>
<tr><td>18</td><td>Oxisol</td><td colspan="4">Pasture</td></tr>
<tr><td>19</td><td>Ultisol</td><td colspan="4">Sugarcane</td></tr>
<tr><td>20</td><td>Ultisol</td><td colspan="4">Sugarcane</td></tr>
<tr><td>21</td><td>Ultisol</td><td colspan="4">Sugarcane</td></tr>
<tr><td>22</td><td>Oxisol</td><td colspan="4">Sugarcane</td></tr>
<tr><td>23</td><td>Oxisol</td><td>Pasture</td><td colspan="3">Sugarcane</td></tr>
<tr><td>24</td><td>Oxisol</td><td colspan="4">Sugarcane</td></tr>
<tr><td>25</td><td>Ultisol</td><td colspan="3">Pasture</td><td>Cassava</td></tr>
<tr><td>26</td><td>Ultisol</td><td colspan="3">Pasture</td><td>Cassava</td></tr>
<tr><td>27</td><td>Ultisol</td><td colspan="2">Pasture</td><td colspan="2">Cassava</td></tr>
<tr><td>28</td><td>Oxisol</td><td colspan="2">Pasture</td><td colspan="2">Cassava</td></tr>
<tr><td>29</td><td>Oxisol</td><td colspan="3">Pasture</td><td>Cassava</td></tr>
<tr><td>30</td><td>Oxisol</td><td colspan="3">Pasture</td><td>Cassava</td></tr>
<tr><td>31</td><td>Ultisol</td><td>Sugarcane</td><td colspan="3">Annual crop</td></tr>
<tr><td>32</td><td>Ultisol</td><td colspan="3">Sugarcane</td><td>Annual crop</td></tr>
<tr><td>33</td><td>Ultisol</td><td colspan="2">Pasture</td><td colspan="2">Annual crop</td></tr>
<tr><td>34</td><td>Oxisol</td><td>Sugarcane</td><td colspan="3">Annual crop</td></tr>
<tr><td>35</td><td>Oxisol</td><td>Pasture</td><td colspan="3">Annual crop</td></tr>
<tr><td>36</td><td>Oxisol</td><td colspan="3">Pasture</td><td>Annual crop</td></tr>
</table>

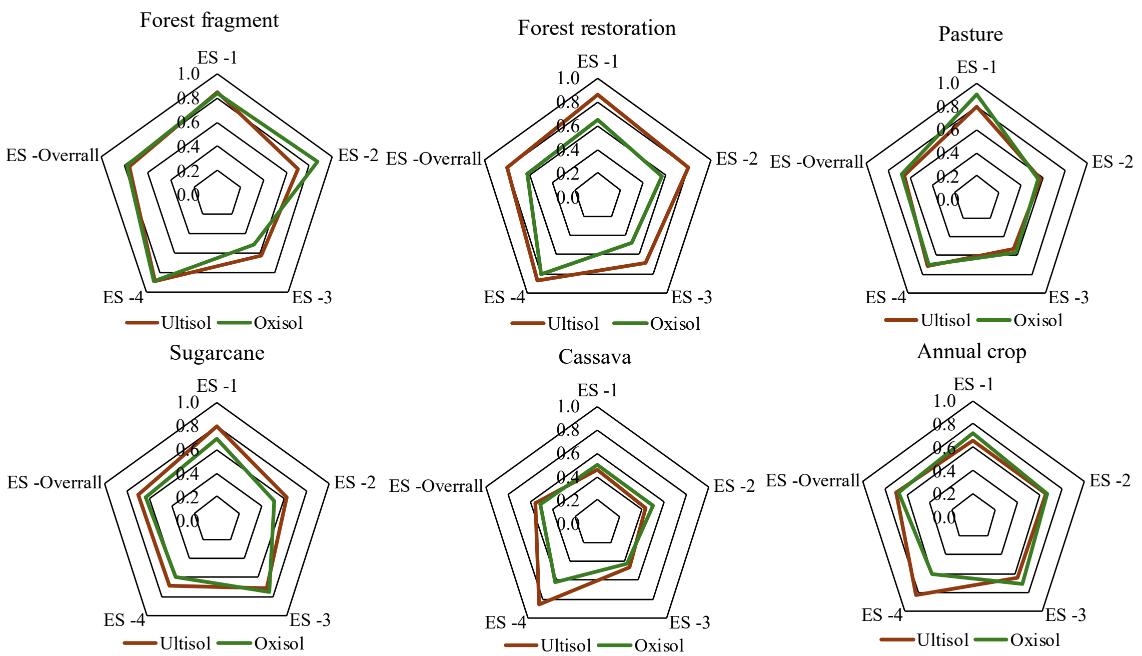


Fig. S. 1. Ecosystem service index provided by the land uses in the Pontal do Paranapanema region – Atlantic Rainforest, SP, Brazil. Note: Carbon stock (SE-1), C cycling (SE2), Soil fertility (SE3), soil structure and water regulation (SE4).

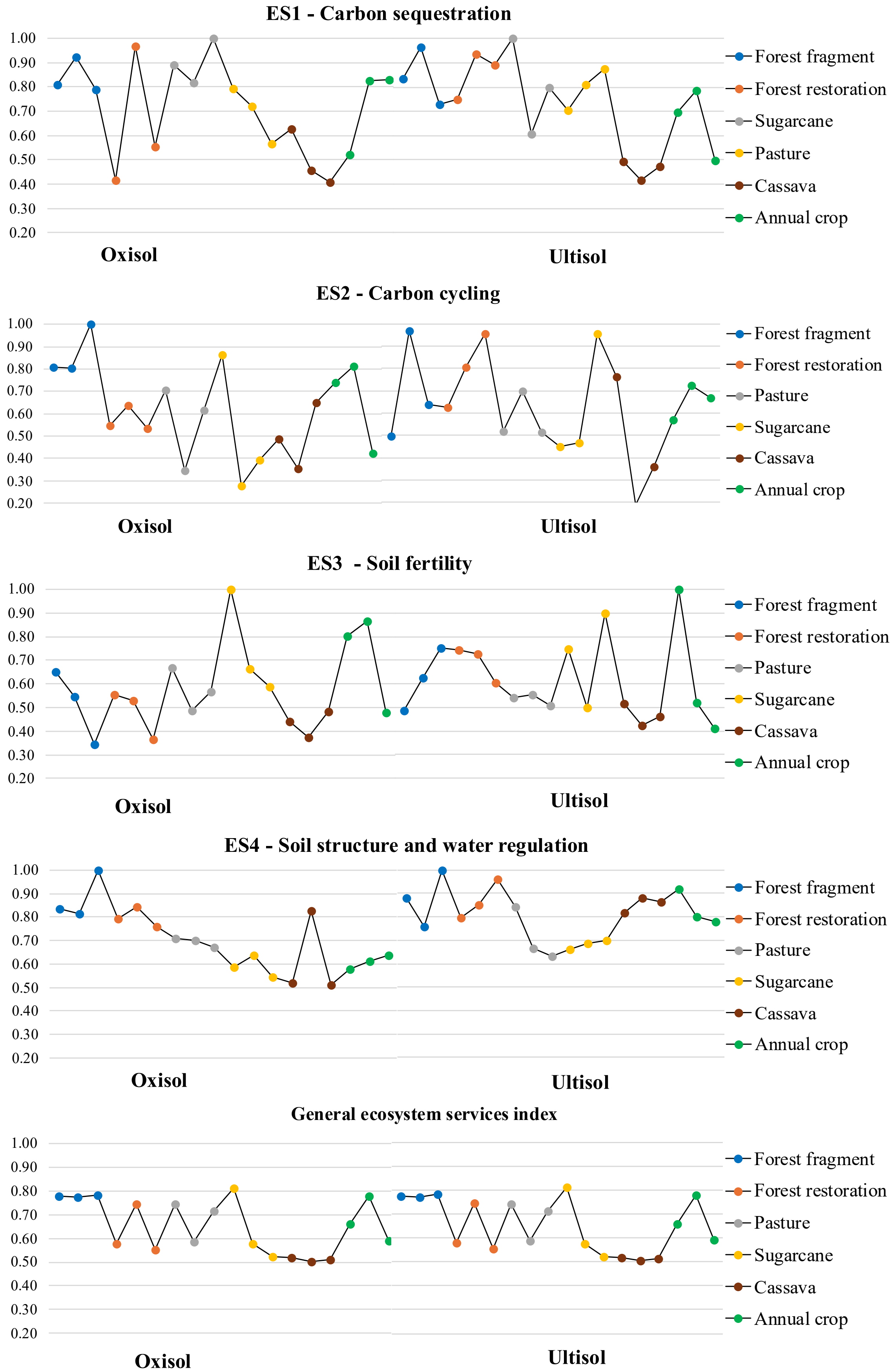


Fig. S. 2. Variability between replicates of the ecosystem service of soils

Table S 2. Ecosystem service index provided by the land uses in the Pontal do Paranapanema region – Atlantic Rainforest, SP, Brazil.

Land Use	**ES 1**		**ES 2**		**ES 3**		**ES 4**		**ES - Overall**	
Forest fragment	0.698	a	0.813	a	0.431	a	0.864	a	0.701	a
Forest restoration	0.687	ab	0.749	ab	0.485	a	0.800	ab	0.680	ab
Pasture	0.683	ab	0.709	ab	0.490	a	0.693	bc	0.644	ab
Sugarcane	0.728	a	0.602	ab	0.687	a	0.631	c	0.662	a
Cassava	0.436	b	0.495	b	0.446	a	0.728	abc	0.526	b
Annual crop	0.642	ab	0.622	ab	0.627	a	0.713	abc	0.651	ab
Soil										
Oxisol	0.636	a	0.715	a	0.509	a	0.671	b	0.633	a
Ultisol	0.653	a	0.615	a	0.546	a	0.805	a	0.655	a

Note: Carbon stock (ES 1), C cycling (ES 2), Soil fertility (ES 3), soil structure and water regulation (ES 4). Note. Means followed by the same letter are not statistically different ($p>0.5$).

Table S 3. Mean comparison test of the attributes used to compose the ecosystem services index.

	Oxisol						Ultisol					
	F. Fragment	**F. Restoration**	**Pasture**	**Sugarcane**	**Cassava**	**Annual crop**	**F. Fragment**	**F. Restoration**	**Pasture**	**Sugarcane**	**Cassava**	**Annual crop**
SOC (%)	1.04a	0.46bc	0.85ab	0.59abc	0.47bc	0.51bc	0.60abc	0.86ab	0.54bc	0.67abc	0.27c	0.48bc
C Stock (Mg.ha)	17.83a	12.29a	21.55a	19.83a	11.80a	14.72a	15.37a	20.55a	14.67a	18.68a	8.96a	14.63a
C Particulate (%)	0.47a	0.52a	0.62a	0.29a	0.23a	0.47a	0.33a	0.27a	0.50a	0.32a	0.18a	0.22a
C mineral (%)	1.91a	2.15a	2.48a	1.62a	1.64a	1.76a	2.32a	2.29a	1.91a	1.95a	1.55a	1.90a
C of Microbial Biomass	595.5a	178.6ab	480.9ab	377.1ab	203.6ab	374.1ab	356.1ab	305.2ab	302.6ab	237.7ab	98.6b	181.1ab
Basal respiration	95.73a	80.14a	63.27a	51.69a	60.74a	54.52a	67.64a	95.09a	53.22a	60.36a	46.89a	66.13a
Glucosidase	236.12a	93.97a	123.91a	129.99a	102.19a	194.60a	147.50a	174.78a	98.69a	101.57a	61.92a	100.94a
QCo2	0.16a	0.93a	0.14a	0.16a	0.32a	0.16a	0.27a	0.32a	0.21a	0.51a	0.70a	0.42a
ph	4.87a	4.70a	5.70a	6.13a	5.37a	6.07a	4.97a	4.93a	5.97a	5.67a	5.37a	6.13a
K	7.23a	21.16a	13.71a	8.12a	0.00a	57.43a	41.42a	67.12a	3.75a	8.06a	4.56a	46.55a
P	1.89 to	2.06a	2.53a	34.38a	2.69a	22.96a	1.27a	5.22a	2.30a	15.75a	1.63a	6.57a
Na	2.33a	4.67a	5.00a	6.67a	3.00a	4.67a	2.67a	4.33a	3.00a	3.67a	2.00a	3.33a
Ca	0.81a	0.63a	1.00a	2.49a	1.00a	2.20a	1.40a	1.24a	1.01a	2.08a	0.91a	1.86a
Mg	0.55a	0.40a	0.73a	1.25a	0.48a	0.84a	0.65a	0.84a	0.77a	1.03a	0.66a	0.75a
Al	0.47a	0.30a	0.10a	0.10a	0.10a	0.17a	0.33a	0.17a	0.10a	0.17a	0.10a	0.10a
H+Al	2.83ab	2.13abc	1.80abc	1.10abc	0.93c	1.47abc	2.87a	2.40abc	1.10abc	1.53abc	1.00c	1.07bc
SB	1.38a	1.08a	1.77a	3.77a	1.48a	3.19a	2.07a	2.25a	1.79a	3.13a	1.59a	2.72a
Effective CEC	1.85a	1.38a	1.87a	3.87a	1.58a	3.35a	2.40a	2.42a	1.89a	3.30a	1.69a	2.82a
CEC pH 7	4.22a	3.21a	3.57a	4.87a	2.42a	4.65a	4.93a	4.65a	2.89a	4.67a	2.59a	3.79a
BS	32.48a	33.99a	49.34a	75.69a	60.90a	65.19a	40.58a	48.78a	62.44a	62.90a	60.52a	63.91a
Sat Al	31.05a	22.68a	5.43a	2.87a	6.54a	7.03a	18.82a	6.92 to	5.38a	8.12a	6.29a	5.33a

P-Rem	46.67a	57.00a	52.90a	48.17a	55.63a	53.60a	50.10a	51.90a	59.27a	53.10a	57.97a	52.90a
N (%)	0.22a	0.12abc	0.19ab	0.15abc	0.11bc	0.13abc	0.15abc	0.20ab	0.12abc	0.15abc	0.07c	0.11bc
Bulk density	1.18c	1.52ab	1.52ab	1.75a	1.52ab	1.58ab	1.34bc	1.54ab	1.55ab	1.57ab	1.60ab	1.63ab
GMD	0.92a	0.77a	1.08a	0.66a	0.88a	0.61a	0.77a	0.74a	0.67a	0.51a	0.57a	0.79a
MWD	1.75a	1.51a	1.97a	1.66a	1.70a	1.39a	1.46a	1.67a	1.53a	1.41a	1.31a	1.84a
Infiltration cm/s	1.90a	2.73a	4.30a	4.43a	2.76a	4.33a	1.73a	4.20a	3.90a	5.15a	7.13a	6.50a
Ks	218.3a	181.7a	32.6cd	16.6d	30.4cd	39.2cd	103.2b	64.8bcd	43.2bcd	28.7cd	84.1bc	36.0cd
Microporosity	0.15bc	0.27ab	0.12bc	0.11c	0.15bc	0.11c	0.32a	0.20abc	0.12bc	0.10c	0.21abc	0.22abc
Macroporosity	0.30a	0.12b	0.20ab	0.18ab	0.16ab	0.21ab	0.14ab	0.18ab	0.18ab	0.18ab	0.12b	0.12b
Total porosity	0.46a	0.40ab	0.32ab	0.30b	0.31b	0.32b	0.45a	0.39ab	0.30b	0.27b	0.33ab	0.34ab
SRP	2.15a	3.27a	1.82a	3.04a	2.35a	3.92a	5.42a	1.54a	3.43a	1.87a	1.63a	2.05a

Subtitle: **SOC** = soil organic carbon; **C stock** = stock C**; QCo2** = metabolic quotient**; pH** = active acidity**; k** = potassium**; P** = phosphorus**; Na** = sodium**; Ca** = calcium**; Mg** = magnesium**; Al** = aluminum**; H + Al** = potential acidity**; SB** = sum of bases; **Effective CEC** = cation exchange capacity**; CEC pH 7** = cation exchange capacity in pH 7; **BS** = Base saturation**; Sat Al = ; P-Rem** = remaining phosphorus**; N** = nitrogen; **MWD** = mean weight diameter; **GMD** = geometric mean diameter**; Ks** = saturated conductivity; **RP** = soil penetration resistance. Note. Means followed by the same letter are not statistically different ($p>0.5$)

Article 3 - Prepared in accordance with NBR 6022 standard	
Article title:	Microbiological indicators as determinant factors of soil quality in coarse-textured tropical soils under distinct land use systems
Authors:	Maria Cecília Vieira Totti Aline Oliveira Silva Sérgio Henrique Godinho Silva Bruno Montoani Silva Fernanda Almeida Bócoli Vanêssa Lopes de Faria Alexandre Uezu Laury Cullen Junior Vinícius Ferreira Fernandes Marco Aurelio Carbone Carneiro Junior Cesar Avanzi

PAPER 3 - MICROBIOLOGICAL INDICATORS AS DETERMINANT FACTORS OF SOIL QUALITY IN COARSE-TEXTURED TROPICAL SOILS UNDER DISTINCT LAND USE SYSTEMS

Maria Cecília Vieira Totti[1,2]; Aline Oliveira Silva[1]; Sérgio Henrique Godinho Silva[1]; Bruno Montoani Silva[1]; Fernanda Almeida Bócoli[1]; Vanêssa Lopes de Faria[1]; Alexandre Uezu[3]; Laury Cullen Junior[3]; Vinícius Ferreira Fernandes[4]; Marco Aurelio Carbone[1]; Carneiro Junior Cesar Avanzi[1*]

[1] Department of Soil Science, Federal University of Lavras, Lavras, Minas Gerais 37203-202, Brazil
[2]Amazonian Research Center CIMAZ-MACAGUAL, University of the Amazon, Florencia 180002, Colombia
[3] Institute for Ecological Research, Faculty for Environmental Conservation and Sustainability, Nazaré Paulista, São Paulo 12960-000, Brazil
[4] Department of Soil and Fertilizer Research, Agronomic Institute of Campinas, Campinas, São Paulo 13020-902, Brazil

*** Corresponding author**. E-mail: junior.avanzi@ufla.br (J. C. Avanzi).

Highlights

- Microbial indicators influence soil quality under different land uses.
- Forested areas have better soil quality than intensive agricultural regions.
- Intensive cropping causes microbial stress and soil compaction.
- Sustainable management preserves soil structure, fertility, and function.

Abstract

Land use alters soil quality, particularly in tropical regions with coarse-textured soils, which are inherently more susceptible to physical and biological degradation. In this context, microbiological indicators represent sensitive and integrative tools to assess changes in soil functionality resulting from different management practices. This study investigates the role of microbiological attributes as key determinants of soil quality across distinct land use systems in the Pontal do Paranapanema region, São Paulo. For this purpose, a Soil Quality Index (SQI) was developed using physical, chemical, and microbiological indicators and applied to both conservationist and intensive land-use systems. The results showed that forested areas exhibited superior soil quality, while intensive cropping was associated with increased microbial stress and compaction. In coarse-textured soils, clay content and conservationist management practices, such as annual cultivation under no-till farming, have a significant positive influence on soil quality improvement. The microbiological indicators, microbial biomass carbon, β-glucosidase activity, basal respiration, and metabolic quotient, as well as physical indicators such as bulk density and porosity, and chemical indicators, such as N content and Mg, were highly responsive to land use, reflecting changes in the biological functioning of the soil. Integrating these indicators into soil quality assessments enhances our understanding of biological processes and their relevance to the sustainability of tropical soils. Canonical correlation analysis confirmed the strong predictive power of microbiological indicators in distinguishing soil quality across land use systems. These findings reinforce the importance of adopting sustainable agricultural practices to preserve soil structure, microbial communities, and overall ecosystem resilience of tropical soils.

Key-words: Ultisol; Oxisol; Microbial functionality; Intensive cropping systems; Sustainable management.

1 Introduction

Soil quality plays a crucial role in managing agricultural productivity and environmental sustainability (Rehman et al., 2022). According to Karlen et al. (1997), soil quality is defined as the capacity of a specific soil type to perform its functions, within the limits of a natural or managed ecosystem, to sustain plant and animal productivity, maintain or improve water and air quality, and support human health and well-being.

Soil quality assessment is carried out by measuring indicators, which represent measurable soil attributes and processes with high sensitivity to changes in their functions and the ecosystem services they provide (Doran & Zeiss, 2000; Silva et al., 2018). In this context, the use of soil quality indicators has proven to be an effective tool for assessing soil functionality and the sustainability of management systems (Cherubin et al., 2016).

Microbiological indicators have stood out as important tools for assessing soil quality and health, offering an integrated perspective on soil dynamics and resilience (Vogel et al., 2022). According to Doran & Zeiss (2000), soil microbiology is a key component for understanding biogeochemical processes and ecological relationships occurring in the terrestrial environment. Microbiological and biochemical indicators are among the most sensitive and show rapid responses to changes in soil management when compared to chemical and physical indicators (Cardoso & Andreote, 2016). Indicators such as microbial biomass carbon (MBC), basal respiration (BR), and genetic diversity reflect the implications of management practices and the soil's capacity to respond to environmental impacts (Vogel et al., 2022).

The use of physical indicators is essential for the quantification of soil health and quality, which is based on the evaluation of the participating attributes of the processes involved with the development of agricultural crops (Vicente et al., 2012). The most frequently analyzed are soil porosity, bulk density, aggregation, pore distribution, aggregate stability, and soil resistance to penetration (Lana et al., 2017). Soil chemical attributes are also essential for assessing soil health and functionality, directly influencing agricultural productivity and environmental sustainability. According to Nortcliff (2002), soil fertility, determined by elements such as pH, N, K, and other nutrients, affects microbial activity and plant growth.

The development of soil quality indices (SQIs) that integrate physical, chemical, and especially microbiological indicators has been identified as an efficient approach to determine the impact of management practices on soil health (Doran & Zeiss, 2000). These indices are particularly useful for guiding management decisions and promoting agro-environmental sustainability (Barbosa et al., 2023; Lal, 1999).

In coarse-textured soils, the inclusion of microbiological indicators in SQI assessments provides more detailed insights into the interactions between biological components and soil resilience (Andrews et al., 2004). In these soils, the physical structure has a lower capacity to retain water and nutrients, which makes maintaining the functionality and productivity of agricultural ecosystems even more challenging (Wei et al., 2023).

Management practices under different land uses play a decisive role in determining soil quality, directly impacting microbiological processes and the soil's resilience capacity (Bhattacharyya et al., 2022). In sandy soil, nutrient retention is impaired; therefore, appropriate management practices can enhance biological processes, resulting in greater stability and sustainability (Andrews et al., 2004).

Thus, understanding the effects of land use and management and their relationship with microbiological indicators and the SQI is fundamental for designing strategies that lead to more efficient and resilient agriculture in the face of climate change and environmental challenges (Bhattacharyya et al., 2022). This study aims to explore this relationship by evaluating the influence of microbiological indicators on the quality of coarse-textured soils under different land uses, based on the construction of a soil quality index. This research hypothesizes that microbiological indicators respond sensitively to variations in land use, regardless of use and cover, and can be used as reliable parameters of soil health in naturally fragile environments.

2 Materials and Methods

2.1 Study Area and Soil Sampling

The study was conducted in the Pontal do Paranapanema region, located in the far west of São Paulo State, Southeastern Brazil, encompassing the municipalities of Teodoro Sampaio, Euclides da Cunha Paulista, Sandovalina, and Mirante do Paranapanema (Fig. 1). According to the Köppen climate classification, the region exhibits two predominant climate types: Aw and Cwa, with annual temperatures ranging between 11 °C and 37 °C. The area is characterized by a dry winter and a rainy summer and is part of the Atlantic Forest biome.

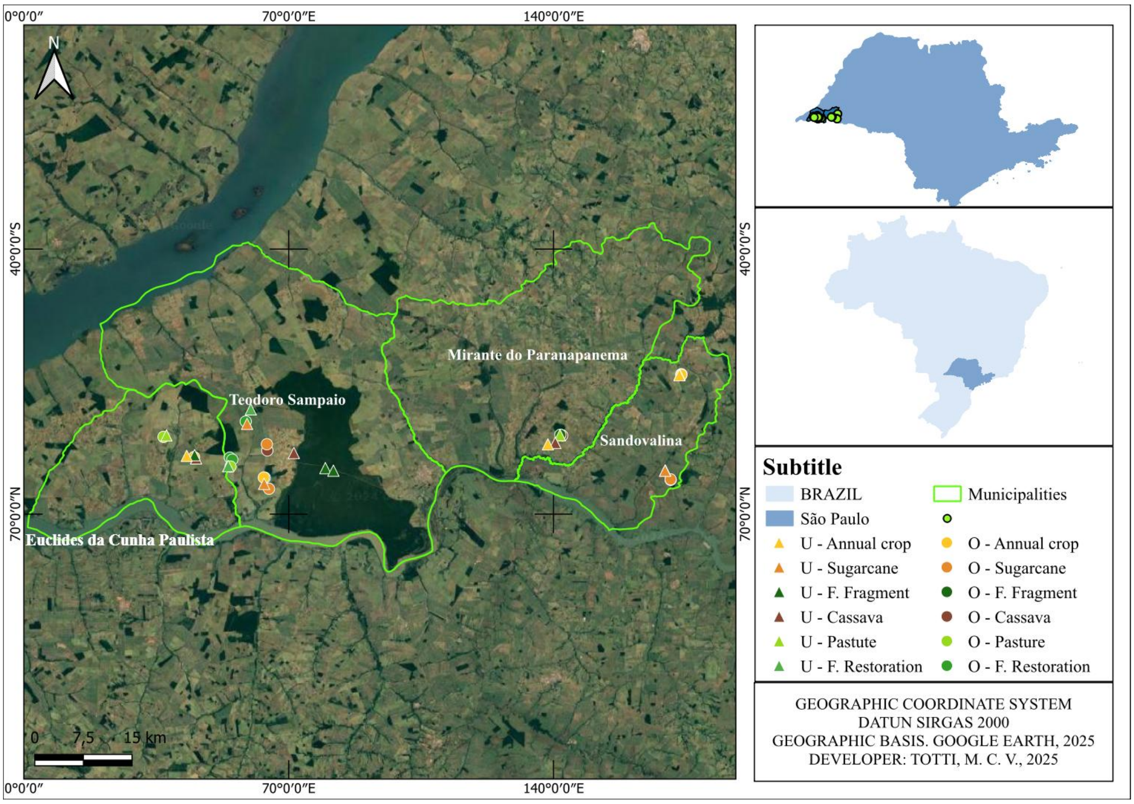


Fig 1. Location of the sampling points in the Pontal do Paranapanema region, São Paulo State, Brazil. Sourse: Totti et al. (2025).

To select the sampling areas, the soil map of São Paulo state (Rossi, 2017) was used to identify the dominant soil types in the region. The main soils in the study area are classified according to the Brazilian Soil Classification System (Santos, 2018) as Red Latossolo and Red Argissolo, and according to the USDA Soil Taxonomy (Soil Survey Staff, 2014) as Oxisols and Ultisols. The most common land use systems in the region were also identified (Fig. 2): 1) Forest fragment (Semideciduous forest), 2) Forest restoration (secondary forest), 3) Pasture with terraces as a conservation practice, 4) Sugarcane, 5) Cassava, and 6) Annual crop (soybean/corn). The forest restoration areas are 15 to 20 years old and were established by planting seedlings of local native species, aiming to preserve the original genetic pool (Mendes et al., 2021).

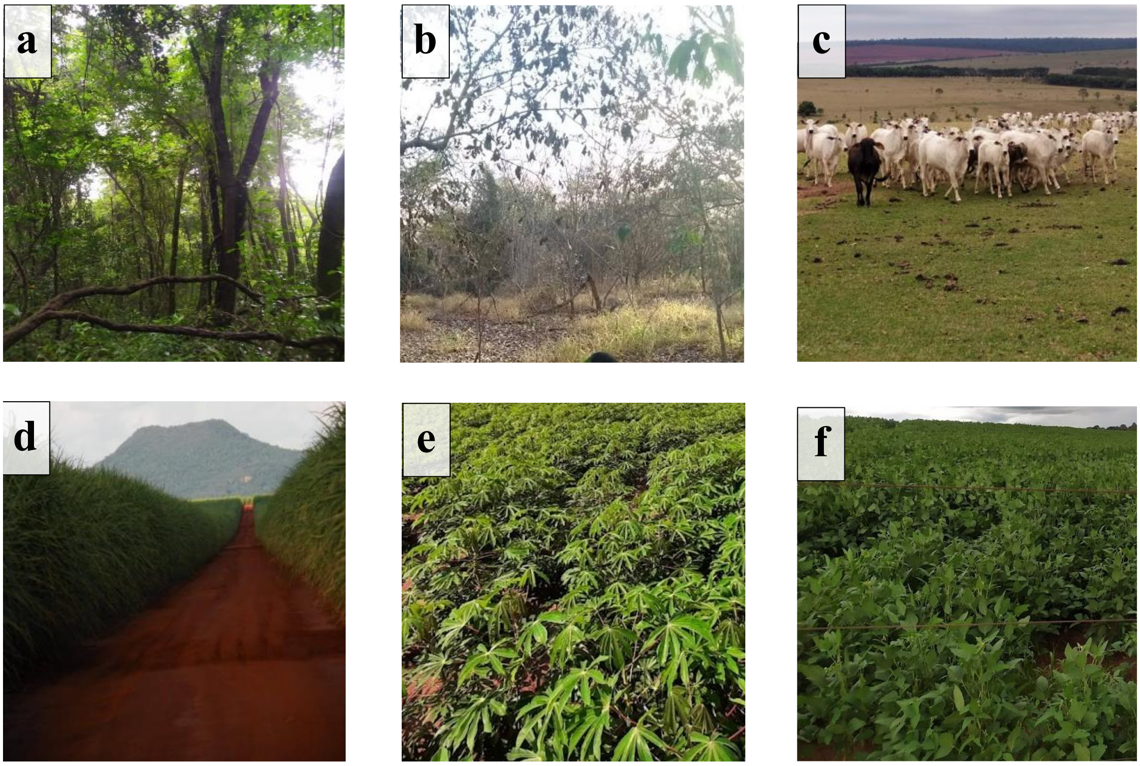


Fig 2. Predominant land uses in the Pontal do Paranapanema region. a) Forest fragment; b) Forest restoration; c) Pasture; d) Sugarcane; e) Cassava; f) Annual crop.

A total of 36 sampling points were selected, based on the combination of two soil types and six soil uses, with three replications per combination. Soil samples were randomly collected in the 0–20 cm layer in February 2023, during the rainy season. Composite samples with the structure not preserved were collected to perform the analyses of texture, chemical, and microbiological attributes of the soil, and aggregate stability. The samples with the preserved structure were collected in volumetric rings of 5 cm wide by 2.5 cm high for analysis of apparent density, macro, micro, and total porosity, and volumetric rings of 5 cm wide by 6 cm high to perform the analysis of saturated conductivity. In addition to this, soil resistance to penetration and infiltration rate in situ were analyzed.

2.2 Soil Attributes

2.2.1 Physical Indicators

Soil particle size (sand, silt, and clay fractions) was determined using the pipette method with a 0.1 mol L^{-1} sodium hydroxide (NaOH) solution as a dispersant. Soil bulk density was calculated based on the dry soil mass. Total porosity was measured using the tension table method. Saturated hydraulic conductivity (Ks) was determined using the constant head permeameter method. Both methods followed Blake e Hartge, (1986).

Aggregate stability was assessed using the wet sieving method proposed by Kemper and Chepil (1965), and the geometric mean diameter (MGD) and mean weight diameter (MWD) of aggregates were calculated according to Wendling et al. (2005). Soil penetration resistance (PR) was measured using an impact penetrometer and calculated following Stolf et al. (2014). Water infiltration rate (In) was evaluated using the Mini Disk Infiltrometer (Zhang, 1997).

2.2.2 Chemical Indicators

Soil pH ($CaCl_2$ 0.01 mol L^{-1}), available phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), potential acidity (H+Al), sum of bases (SB), cation exchange capacity (CEC), base saturation (V%), and soil organic matter (SOM) were determined following Teixeira et al. (2017).

2.2.3 Microbiological and Organic Matter Indicators

Microbial biomass carbon (MBC) was determined using the fumigation-extraction method (Vance et al., 1987). Basal respiration (BR) was measured according to Alef and Nannipieri (1995). β-glucosidase activity was determined through the colorimetric method using β-glucoside (BG) as substrate (Dick et al., 2015). The metabolic quotient (qCO_2) was calculated as the ratio of BR to MBC (Anderson & Domsch, 1993). Soil organic matter fractionation was performed according to Leuthold et al. (2023).

2.3 Data Analysis

The goal of the statistical analysis was to evaluate the influence of microbiological attributes on the quality of coarse-textured soils in Pontal do Paranapanema, under different land uses. Initially, a Soil Quality Index (SQI) was constructed, following the methodology proposed by Cherubin et al. (2016), adapted to the attributes assessed in this study.

2.3.1 Correlation Analysis

For each soil type, Pearson correlation analysis was performed among all microbiological indicators, organic matter fractions, and physical and chemical attributes. This analysis aimed to identify which attributes were most strongly associated with soil quality for each condition. Significant correlations were used to inform subsequent multivariate analyses.

2.3.2 Canonical Correlation Analysis (CCA)

Based on the results from the correlation analysis, a Canonical Correlation Analysis (CCA) was carried out. This analysis was conducted to understand how physical and chemical soil indicators respond to microbiological indicators. In this analysis, the microbiological indicators (microbial biomass carbon, basal respiration, β-glucosidase activity, and metabolic quotient) and organic matter fractions (Particulate Organic Matter – POM, and Mineral-Associated Organic Matter – CAM) were defined as predictor variables. The response variables consisted of the chemical and physical attributes that had shown the highest correlations with the predictors in the previous step. This multivariate approach enabled exploration of the complex relationships between microbial activity and soil physicochemical conditions across different land uses.

2.3.3 Pearson Correlation Analysis (Individual)

Lastly, individual Pearson correlation analyses were conducted between the microbiological indicators and the organic matter fractions, and with the most strongly correlated physical variables: sand, clay, and bulk density. This step complemented the multivariate analyses by offering a more detailed understanding of specific relationships, especially regarding how soil texture and structure affect organic matter dynamics and microbial activity, key aspects in the functioning of coarse-textured soils. The analysis aimed to evaluate the performance of microbiological attributes as indicators of soil quality under different land uses.

A Duncan test was applied to test for statistical differences between the soil quality index averages. Statistical analyses were carried out in R software version 4.4.2 (R Core Team, 2023), using the R Studio integrated development environment version 2024.09.1+394 (RStudio Team, 2023).

2.3.4 Soil Quality Index (SQI)

The index was constructed based on data standardization (z-score), selection of indicators sensitive to soil management, and aggregation through Principal Component Analysis (PCA). The construction of the Soil Quality Index is described in four main steps:

2.3.4.1 Selection of indicators

Physical, chemical, microbiological, and organic matter-related soil attributes were selected based on their relevance in literature and sensitivity to soil management.

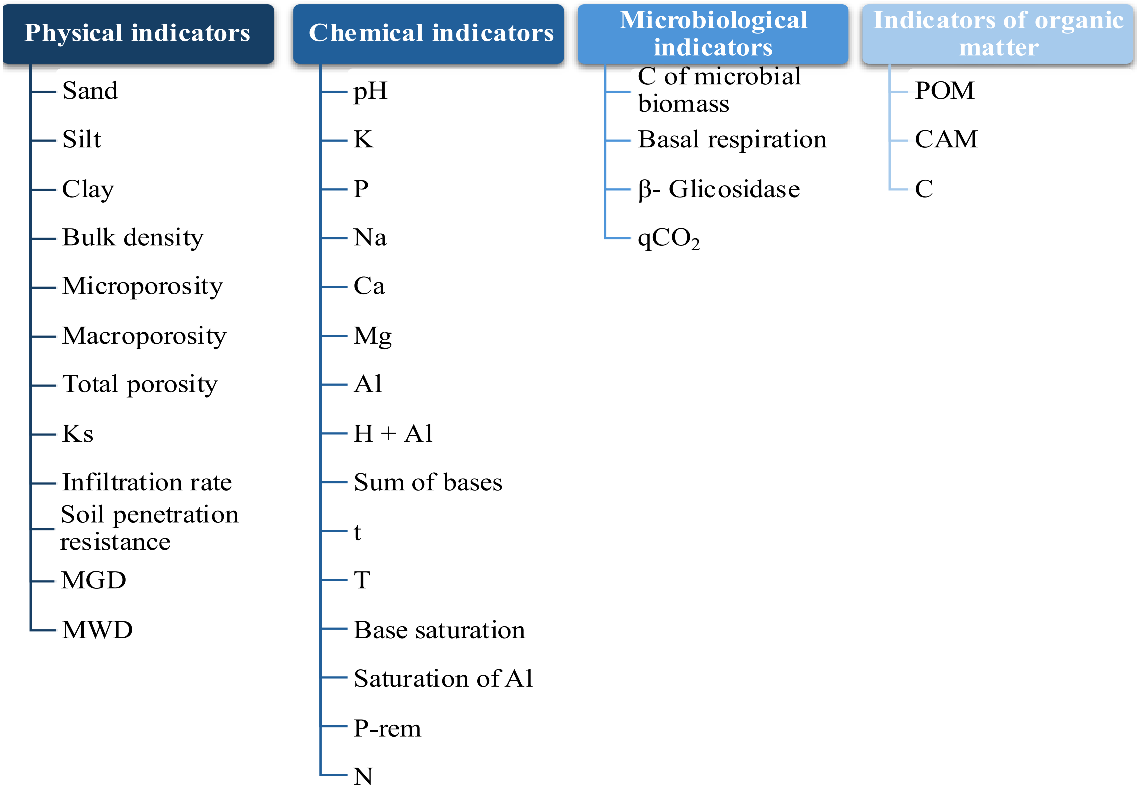


Fig. 3 summarizes the chosen indicators. Subtitle: C = soil organic carbon; POM = C Particulate; CAM = C mineral; qCO_2 = metabolic quotient; pH = active acidity; k = potassium; P = phosphorus; Na = sodium; Ca = calcium; Mg = magnesium; Al = aluminum; H + Al = potential acidity; SB = sum of bases; Effective; BS = Base saturation; Sat Al = ; P-Rem = remaining phosphorus; N = nitrogen; MWD = mean weight diameter; MGD = geometric mean diameter; Ks = saturated conductivity; PR = soil penetration resistance.

2.3.5 Data normalization

Each indicator was normalized using the min-max linear transformation:

$$X\ norm = \frac{x - xmin}{xmax - xmin} \qquad (1)$$

For indicators where higher values indicate better soil quality (e.g., organic carbon, infiltration rate, CEC), this equation was applied directly. For indicators where lower values are preferable (e.g., bulk density, qCO_2), the equation was inverted, following Cherubin et al. (2016).

2.3.6 Weighting by PCA

Principal Component Analysis (PCA) was used to reduce data dimensionality and assign weights to indicators according to their contribution to each principal component. Variables with the highest loadings were retained, and weights were determined in proportion to the variance explained.

2.3.7 Final index calculation

The SQI for each land use within each soil type was calculated using the following formula:

$$Spca = \sum_{i=1}^{n} Scorei \text{ x } Pesoi \quad (2)$$

where $Weight_i$ corresponds to the relative contribution of each variable in the PCA. This model allows for a more objective capture of the interrelationships among the indicators and their respective contributions to soil quality variability. To obtain a value for each land use, the average of the three replicates was calculated. Subsequently, the mean of the six land uses was computed to provide a general overview of the quality of the soils studied.

3 Results and Discussion

3.1 Correlation Analysis

The correlation analysis was applied to the soil attributes under study to highlight significant differences and similarities between Ultisol and Oxisol, emphasizing their physical, chemical, and microbiological characteristics and responses to environmental conditions. The Fig. 4. shows the 19 attributes of each soil with the highest correlations. (i.e. >0.65 and <-0.65). Regarding chemical resilience, Ultisol showed greater vulnerability to acidity, with correlations between pH and aluminum saturation (-0.61), indicating chemical challenges in more acidic soils (Li et al., 2022). In contrast, Oxisol demonstrated higher chemical resilience, with positive correlations between pH and attributes such as calcium (Ca: 0.85) and base saturation (0.88), highlighting its greater chemical fertility (Bhunia et al., 2021).

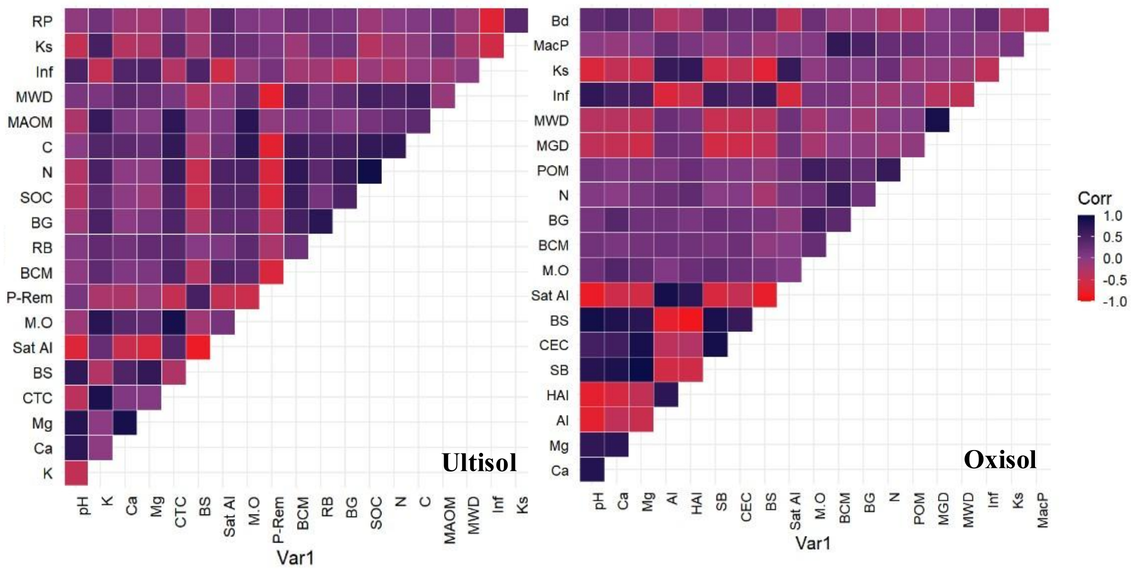


Fig. 4. Correlation analysis between physical, chemical, and microbiological attributes of Ultisols and Oxisols from the Pontal do Paranapanema region, São Paulo. Subtitle: C = soil organic carbon; POM = particulate carbon; CAM = mineral carbon; qCO_2 = metabolic quotient; pH = active acidity; k = potassium; P = phosphorus; Na = sodium; Ca = calcium; Mg = magnesium; Al = aluminum; H + Al = potential acidity; SB = sum of bases; Effective; BS = base saturation; Sat Al = aluminum saturation; P-Rem = remaining phosphorus; N = nitrogen; MWD = mean weighted diameter; MGD = mean geometric diameter; Ks = saturated conductivity; PR = soil penetration resistance.

In terms of physical structure, both soils showed signs of compaction due to their predominantly fine sand texture (Yu et al., 2024), with strong correlations between density and total porosity (-0.53) and penetration resistance (0.54) in Ultisol, and between saturated conductivity (-0.64) and total porosity (-0.72) in Oxisol. Regarding microbiological activity, in the Ultisol, MBC showed a positive correlation with Al (0.63), indicating potential microbial adaptation with probable impacts on soil microbiological health (Vogel et al., 2022). Meanwhile, in Oxisol, MBC exhibited positive correlations with macroporosity (0.69) and nitrogen (N: 0.63), revealing a biologically active soil well-integrated into nutrient cycles (Bhattacharyya et al., 2022).

3.2 Pearson correlation analysis

Pearson's correlation analysis was applied between microbiological attributes (MBC, BR, BG, and qCO_2) and granulometric fractions (sand and clay), soil organic matter fractions (CAM and POM), and bulk density (Bd), considering land use. The analysis aimed to evaluate the performance of microbiological attributes as indicators of soil quality under different land uses.

The analysis (Fig. 5) revealed distinct behaviors of microbiological attributes to Ultisol land uses. Soil microbial biomass carbon (MBC) was positively correlated with clay and bulk density. This indicates that higher clay content favor microbial activity (Bonetti et al., 2017). Conversely, MBC decreased as the sand proportion increased, suggesting that sandier textures may restrict the retention of water and nutrients essential for microbiota (Wei et al., 2023). In intensive cultivation areas, such as sugarcane, pasture, and cassava, qCO_2 was higher, indicating metabolic stress (Bonetti et al., 2017). On the other hand, in forest fragments and forest restoration areas, lower qCO_2 values pointed to a more balanced environment for microbial communities (Meena & Rao, 2021).

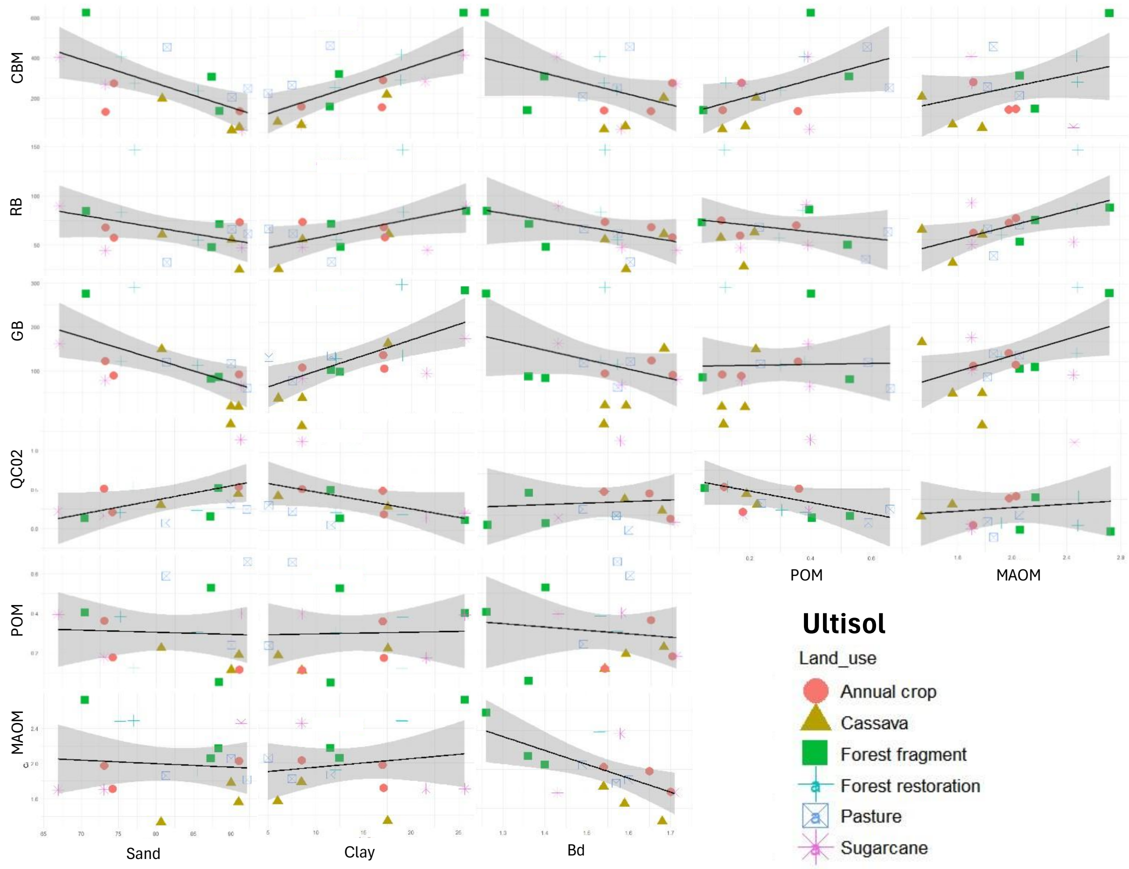


Fig. 5. Pearson correlation analysis of Ultisol under different land uses in the Pontal do Paranapanema region, São Paulo. Subtitle: POM = particulate carbon; CAM = mineral carbon; qCO_2 = metabolic quotient.

The Pearson correlation applied to Oxisol (Fig. 6) showed that MBC tends to increase with clay and slightly decrease with sand, suggesting that clayier soils support greater microbial biomass (Xia et al., 2020). There was a weak negative correlation with Bd, indicating that soil compaction might not severely limit microbial activity up to a certain threshold (Valpassos et al., 2001). BR showed positive correlations with CAM and clay, implying that in clay-rich soils, microbial respiration is higher, representing both increased activity and metabolic stress (Bonetti et al., 2017). BG was negatively correlated with Bd and positively associated with CAM, indicating that soils richer in mineralized organic matter promote greater enzymatic activity (Wei et al., 2023). Meanwhile, the metabolic quotient increases with sand, which could be interpreted as microbial stress in compacted, clay-deficient soils (Cotrufo et al., 2022).

These results highlight how land uses individually influence microbiological attributes, emphasizing the importance of management practices that preserve organic matter and soil structure to promote microbial health. Moreover, they highlight microbiological indicators as sensitive and practical tools for detecting the impacts of land use on tropical soil quality.

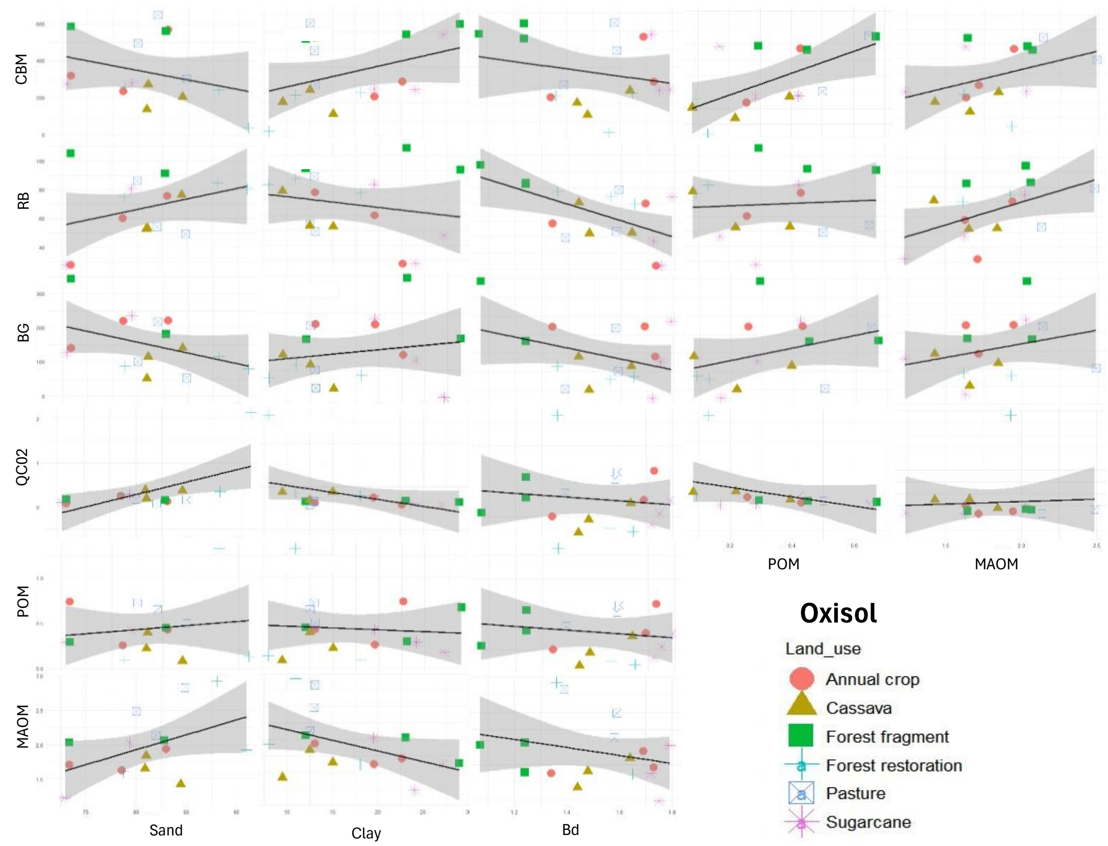


Fig. 6. Pearson correlation analysis of Oxisol under different land uses in the Pontal do Paranapanema region, São Paulo. Subtitle: POM = particulate carbon; CAM = mineral carbon; qCO_2 = metabolic quotient.

3.3 Canonical Correlation Analysis (CCA)

The results obtained from the canonical correlation analysis, applied to the 20 attributes with the highest correlations for each soil (Fig. 7), are presented in Fig. 4. This analysis was conducted to understand how physical and chemical soil indicators respond to microbiological indicators. Therefore, microbiological and organic matter-related indicators (MBC, BG, RB, qCO_2, CAM, and POM) were used as predictors.

The CCA demonstrated that microbiological attributes play a key role in differentiating soil quality among the land uses studied. For Ultisol, the first canonical axis explained 99% of the variation, whereas in Oxisol, the first axis explained 98%. In Ultisol, conservationist land uses, particularly forest fragment and forest restoration, were close to high-quality soil indicators such as organic matter fractions (CAM and POM), soil microbial biomass carbon (MBC), and Beta-glucosidase (BG), exhibiting a positive gradient of soil health (Doran & Zeiss, 2000). This suggests that areas under these uses support more active microbial communities with greater efficiency in carbon cycling (Bhattacharyya et al., 2022).

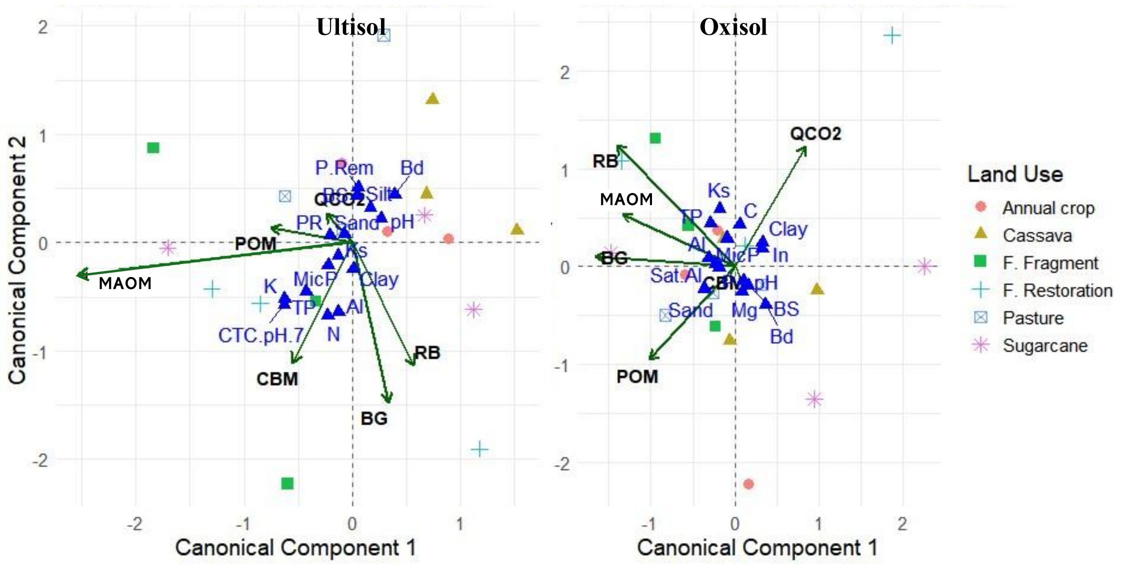


Fig. 7. Canonical correlation analysis for Ultisol and Oxisols under different land uses in the Pontal do Paranapanema region, São Paulo. Subtitle: C = soil organic carbon; POM = particulate carbon; CAM = mineral carbon; qCO_2 = metabolic quotient; pH = active acidity; k = potassium; P = phosphorus; Na = sodium; Ca = calcium; Mg = magnesium; Al = aluminum; H + Al = potential acidity; SB = sum of bases; Effective; BS = base saturation; Sat Al = aluminum saturation; P-Rem = remaining phosphorus; N = nitrogen; MWD = mean weight diameter; MGD = geometric mean diameter; Ks = saturated conductivity; PR = soil penetration resistance.

In contrast, intensive land uses, such as pasture, cassava, and annual crops, aligned with the qCO_2 vector, revealing a potential decline in microbial efficiency (Meena & Rao, 2021), corroborating the SQI results. In Oxisols, the CCA indicated greater sensitivity to soil management impacts, with the same agricultural uses being strongly associated with increases in qCO_2 and soil compaction indicators, such as high bulk density. This highlights reduced microbiological activity and potential soil health degradation under these uses (Gajda et al., 2016). In this context, while Ultisol displays a certain degree of microbial resilience to management practices, Oxisol requires even stricter usage and conservation strategies to maintain soil quality.

3.4 Soil Quality Index

The Soil Quality Index (SQI) (Fig. 8, Table 1) aimed to highlight differences among various land uses and illustrate how soils uniquely respond to management practices. Statistical difference was observed only in the forest fragment use (Tab. 1) between the soils, where Ultisol scored 0.67 and Oxisol scored 0.72. The limited number of statistical differences can be attributed to the high variability among index replicates (Fig. S 1). The forest fragment use presented the highest SQI values, distinguishing itself from other land uses in both soils evaluated. This outcome reflects the essential role of forest cover in maintaining soil structure and functionality (Bhattacharyya et al., 2022), particularly in less resilient soils such as Ultisol (Bonetti et al., 2017).

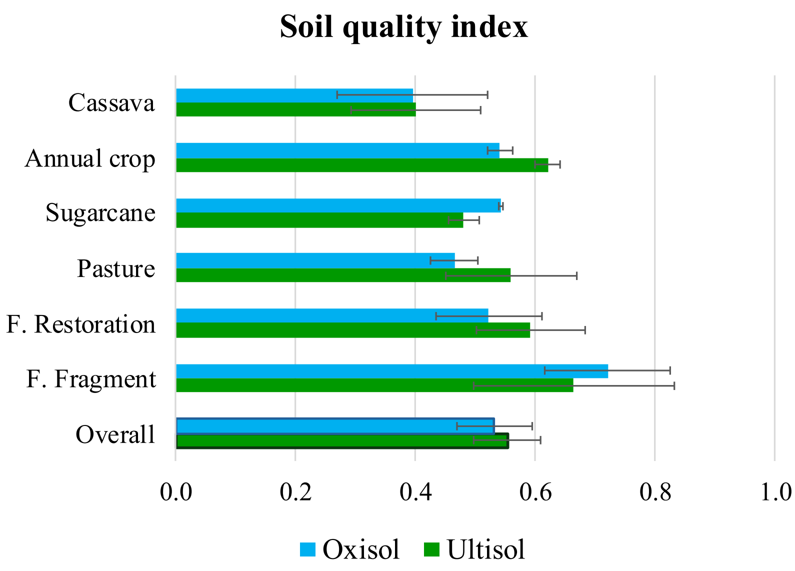


Fig 8. Soil Quality Index applied to Ultisol and Oxisols under different land uses in the Pontal do Paranapanema region, São Paulo.

On the other hand, cassava cultivation areas consistently presented the lowest SQI values, with identical scores in both soils (0.40), also standing out from other land uses. This indicates that intensive agricultural practices, as applied to cassava cultivation, can significantly negatively impact these soil types, which are more susceptible to erosion and nutrient loss (Radhakrishnan et al., 2022).

Table 1. Soil quality index applied to Ultisols and Oxisols, under different uses in the region of Pontal do Paranapanema - SP

Land Use	Ultisol	Oxisol
F. Fragment	0.67 ABa	0.72 Aa
F. Restoration	0.59 ABab	0.52 ABab
Pasture	0.56 ABab	0.47 ABab
Sugarcane	0.48 ABab	0.54 ABab

Cassava	0.40 Bb	0.40 Bb
Annual crop	0.62 ABab	0.54 ABab

Subtitles. Averages followed by uppercase letters differentiate between soils, and averages followed by lowercase letters differentiate between land uses.

Pasture and annual crop areas exhibited significant variation in SQI, especially in Ultisol (pasture: 0.41–0.77 in Ultisol and 0.40–0.54 in Oxisol; annual crop: 0.41–0.77 in Ultisol and 0.40–0.54 in Oxisol). Although conservation management practices can improve soil quality (Zhao et al., 2022), the variability of values indicates that areas with intensive pasture systems and monocultures face a higher risk of soil degradation (Mayel et al., 2021), particularly in Ultisol (Bonetti et al., 2017).

The intensive sugarcane monoculture can reduce soil quality in both soils (Ultisol: 0.48; Oxisol: 0.54) due to intense management, frequently involving heavy machinery (Oliveira et al., 2022). Finally, in forest restoration areas, Oxisol showed an SQI of 0.52, while Ultisol presented an SQI of 0.59, suggesting that Ultisol, due to its sandy texture, might recover structural integrity more rapidly thanks to greater aeration, water infiltration, and microbial activity (Agbeshie et al., 2022), despite the absence of statistical differences between soils.

Overall, SQI revealed that land use type and management systems exert a greater influence on soil quality, as also noted by Silva-Olaya et al. (2022). Meanwhile, soil type and its natural characteristics modulate soil responses to management practices (Bonetti et al., 2017). Given the coarse texture of both soils, greater care in management is required to prevent degradation. These results reinforce the importance of agricultural practices focused on sustainability while respecting the particularities of each soil type and land-use system.

4 Conclusions

This study highlighted the importance of microbiological indicators in evaluating the quality of coarse-textured tropical soils. The Soil Quality Index (SQI) demonstrated that conservationist land uses, such as forest fragments and forest restoration, are directly associated with higher soil quality, with indicators revealing efficient carbon cycling and balanced microbial activities. Conversely, intensive land uses, such as pasture, cassava, and annual crops, exhibited greater metabolic stress and a higher risk of structural degradation.

Microbiological indicators have proven to be essential tools for assessing the quality of naturally fragile tropical soils. Microbial biomass carbon, β-glucosidase, and metabolic quotient are sensitive instruments for identifying the impacts of different land uses on Ultisols and Oxisols. Canonical correlation analysis reinforced the relationship between microbiological attributes and the physical and chemical properties of the soil, demonstrating the effectiveness of these indicators in assessing soil quality.

This study emphasized the interdependence between soil structure and functionality, highlighting the importance of sustainable management practices that preserve organic matter, structure, and biological processes, ensuring the resilience of tropical soils.

Acknowledgments

We acknowledge the financial support of China Three Gorges Corporation (CTG-Brazil), Coordination of Improvement of Higher Education Personnel (CAPES), National Council for Scientific and Technological Development (CNPq) process 406903/2022-0, Foundation for Research Support of the State of Minas Gerais (FAPEMIG) process APQ-01173-24, and Institute for Ecological Research (IPÊ). SHGS, BMS, FAB and JCA thank CNPq for grants number 307532/2022-4, 311743/2021-8, 174948/2023-9, and 307059/2022-7, respectively.

REFERENCES

Agbeshie, A. A., Abugre, S., Atta-Darkwa, T., & Awuah, R. (2022). A review of the effects of forest fire on soil properties. In Journal of Forestry Research (Vol. 33, Issue 5, pp. 1419–1441). Northeast Forestry University. https://doi.org/10.1007/s11676-022-01475-4.

Alef, K., Nannipieri, P., 1995. Methods in applied soil microbiology and biochemistry. https://doi.org/10.5555/19951908199.

Anderson, T.-H., Domsch, K.H., 1993. The metabolic quotient for co, (qC02) as a specific activity parameter to assess the effects of environmental conditions, such as pH, on the microbial biomass of forest soils, Soil Biol. Biochem.

Andrews, S. S., Karlen, D. L., & Cambardella, C. A. (2004). The Soil Management Assessment Framework. Soil Science Society of America Journal, 68(6), 1945–1962. https://doi.org/10.2136/sssaj2004.1945.

Barbosa, J. Z., Poggere, G., Corrêa, R. S., Hungria, M., & Mendes, I. de C. (2023). Soil enzymatic activity in Brazilian biomes under native vegetation and contrasting cropping and management. Applied Soil Ecology, 190. https://doi.org/10.1016/j.apsoil.2023.105014.

Bhattacharyya, S. S., Ros, G. H., Furtak, K., Iqbal, H. M. N., & Parra-Saldívar, R. (2022). Soil carbon sequestration – An interplay between soil microbial community and soil organic matter dynamics. In Science of the Total Environment (Vol. 815). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2022.152928.

Bhunia, S., Bhowmik, A., Mallick, R., & Mukherjee, J. (2021). Agronomic efficiency of animal-derived organic fertilizers and their effects on biology and fertility of soil: A review. In Agronomy (Vol. 11, Issue 5). MDPI AG. https://doi.org/10.3390/agronomy11050823.

Bonetti, J. A., Anghinoni, I., Moraes, M. T., & Fink, J. R. (2017). Resilience of soils with different texture, mineralogy and organic matter under long-term conservation systems. In Soil and Tillage Research (Vol. 174, pp. 104–112). Elsevier B.V. https://doi.org/10.1016/j.still.2017.06.008.

Cardoso, E. J. B. N., & Andreote, F. D. (2016). Microbiologia do solo (ESALQ, Ed.; 2nd ed.). Universidade de São Paulo. Escola Superior de Agricultura Luiz de Queiroz. https://doi.org/10.11606/9788586481567.

Cherubin, M.R., Karlen, D.L., Cerri, C.E.P., Franco, A.L.C., Tormena, C.A., Davies, C.A., Cerri, C.C., 2016. Soil quality indexing strategies for evaluating sugarcane expansion in Brazil. PLoS One 11, 1–26. https://doi.org/10.1371/journal.pone.0150860.

Cotrufo, M. F., Haddix, M. L., Kroeger, M. E., & Stewart, C. E. (2022). The role of plant input physical-chemical properties, and microbial and soil chemical diversity on the formation of particulate and mineral-associated organic matter. Soil Biology and Biochemistry, 168. https://doi.org/10.1016/j.soilbio.2022.108648.

Dick, R.P., Breakwell, D.P., Turco, R.F., 2015. Soil enzyme activities and biodiversity measurements as integrative microbiological indicators, in: Methods for Assessing Soil Quality. wiley, pp. 247–271. https://doi.org/10.2136/sssaspecpub49.c15.

Doran, J. W., & Zeiss, M. R. (2000). Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology, 15(1), 3–11. https://doi.org/10.1016/S0929-1393(00)00067-6.

Gajda, A. M., Czyz, E. A., & Dexter, A. R. (2016). Effects of long-term use of different farming systems on some physical, chemical and microbiological parameters of soil quality. International Agrophysics, 30(2), 165–172. https://doi.org/10.1515/intag-2015-0081.

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE. Soil quality: A concept, definition, and framework for evaluation. Soil Sci Soc Am J. 1997; 61:4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x.

Kemper, W.D., Chepil, W.S., 1965. Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, 9th ed. Madison. https://doi.org/https://doi.org/10.2134/agronmonogr9.1.c39.

Lal, R. (1999). Métodos para a avaliação do uso sustentável dos recursos solo a água nos trópicos (3rd ed.).

Lana, R. M. Q., Domingues, L. A. S., Torres, J. L. R., Mageste, J. G., & Moraes, E. R. (2017). Soil physical attributes and productivity of sugarcane under different cropping systems in the savannah goiano. Australian Journal of Crop Science | Journal Article |, 11, 149–155. https://doi.org/10.3316/informit.821582045447748.

Leuthold, S.J., Haddix, M.L., Lavallee, J., Cotrufo, M.F., 2023. Physical fractionation techniques, in: Encyclopedia of Soils in the Environment, Second Edition. Elsevier, pp. V2-68-V2-80. https://doi.org/10.1016/B978-0-12-822974-3.00067-7.

Li, K. wei, Lu, H. long, Nkoh, J. N., Hong, Z. neng, & Xu, R. kou. (2022). Aluminum mobilization as influenced by soil organic matter during soil and mineral acidification: A constant pH study. Geoderma, 418. https://doi.org/10.1016/j.geoderma.2022.115853.

Mayel, S., Jarrah, M., & Kuka, K. (2021). How does grassland management affect physical and biochemical properties of temperate grassland soils? A review study. In Grass and Forage Science (Vol. 76, Issue 2, pp. 215–244). Blackwell Publishing Ltd. https://doi.org/10.1111/gfs.12512.

Meena, A., & Rao, K. S. (2021). Assessment of soil microbial and enzyme activity in the rhizosphere zone under different land use/cover of a semiarid region, India. Ecological Processes, 10(1). https://doi.org/10.1186/s13717-021-00288-3.

Mendes, L.M., César, R.G., Uezu, A., Beltrame, T.P., Rodriguez, L.C.E., Gomes, H.B., Cullen, L., 2021. Large canopy and animal-dispersed species facilitate natural regeneration in tropical forest restoration. Restor Ecol 29. https://doi.org/10.1111/rec.13406.

Nortcliff, S. (2002). Standardisation of soil quality attributes. Em Agriculture, Ecosystems and Environment (Vol. 88).

Oliveira, I. N. de, Souza, Z. M. de, Bolonhezi, D., Totti, M. C. V., Moraes, M. T. Lovera, L. H., Lima, E. de S., Esteban, D. A. A., & Oliveira, C. F. (2022). Tillage systems impact on soil physical attributes, sugarcane yield and root system propagated by pre-sprouted seedlings. Soil and Tillage Research, 223. https://doi.org/10.1016/j.still.2022.105460.

Radhakrishnan, A. R. S., Suja, G., & Sreekumar, J. (2022). How sustainable is organic management in cassava? Evidences from yield, soil quality, energetics and economics in the humid tropics of South India. Scientia Horticulturae, 293, 110723. https://doi.org/10.1016/j.scienta.2021.110723.

Rehman, A., Farooq, M., Lee, D. J., & Siddique, K. H. M. (2022). Sustainable agricultural practices for food security and ecosystem services. In Environmental Science and

Pollution Research (Vol. 29, Issue 56, pp. 84076–84095). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s11356-022-23635-z.

Rossi, M., 2017. Mapa pedológico do estado de São Paulo: Revisado e ampliado. São Paulo.

Santos, H.G. dos., 2018. Sistema brasileiro de classificação de solos, 5th ed. Embrapa, Brasília, DF.

Silva, A. O., Costa, A. M., Teixeira, A. F. S., Guimarães, A. A., Santos, J. V., Moreira, F. M. S. (2018). Soil microbiological attributes indicate recovery of an iron mining area and of the biological quality of adjacent phytophysiognomies. Ecological Indicators, 93, 142–151. https://doi.org/10.1016/j.ecolind.2018.04.073.

Silva-Olaya, A. M., Ortíz-Morea, F. A., España-Cetina, G. P., Olaya-Montes, A., Grados, D., Gasparatos, A., & Cherubin, M. R. (2022). Composite index for soil-related ecosystem services assessment: Insights from rainforest-pasture transitions in the Colombian Amazon. Ecosystem Services, 57. https://doi.org/10.1016/j.ecoser.2022.101463.

Soil Survey Staff, 2014. Keys to soil taxonomy. Soil Conservation Service 12, 410.
Stolf, R., Murakami, J.H., Brugnaro, C., Silva, L.G., Silva, L.C.F. da, Margarido, L.A.C., 2014. Penetrômetro de impacto stolf - programa computacional de dados em EXCEL-VBA. Rev Bras Cienc Solo 38, 774–782. https://doi.org/10.1590/S0100-06832014000300009.

Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G., 2017. Manual de Métodos de Análise de Solo, 3rd ed, Manual de métodos de análise de solo. Brasília. DF.

Totti, M.C.V., Zinn, Y.L., Silva, S.H.G., Silva, B.M., Bócoli, F.A., Faria, V.L. de, Montes, A.O., Acuña-Guzman, S.F., Uezu, A., Cullen Junior, L., Fernandes, V.F., Avanzi, J.C., 2025. Organic carbon stocks across various land use systems in Sandy Ultisols and Oxisols in Brazil. Geoderma Regional 40. https://doi.org/10.1016/j.geodrs.2025.e00924.

Valpassos, M. A. R., Cavalcante, E. G. S., Cassiolato, A. M. R., & Alves, M. C. (2001). Effects of soil management systems on soil microbial activity, bulk density and chemical properties. Pesquisa Agropecuária Brasileira, 36, 1539–1545.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol Biochem 19, 703–707. https://doi.org/10.1016/0038-0717(87)90052-6.

Vicente, T. S., Pedrosa, E. M. R., Rolim, M. M., Oliveira, V. S., Oliveira, A. K. S., & Souza, A. M. P. L. (2012). Relações de atributos do solo e estabilidade de agregados em canaviais com e sem vinhaça. Revista Brasileira de Engenharia Agrícola e Ambiental, 16, 1215–1222. https://doi.org/–http://www.agriambi.com.br.

Vogel, H. J., Balseiro-Romero, M., Kravchenko, A., Otten, W., Pot, V., Schlüter, S., Weller, U., & Baveye, P. C. (2022). A holistic perspective on soil architecture is needed as a key to soil functions. European Journal of Soil Science, 73(1). https://doi.org/10.1111/ejss.13152.

Wei, B., Peng, Y., Lin, L., Zhang, D., Ma, L., Jiang, L., Li, Y., He, T., & Wang, Z. (2023). Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis. In Geoderma (Vol. 437). Elsevier B.V. https://doi.org/10.1016/j.geoderma.2023.116591.

Wendling, B., Jucksch, I., De, E., Mendonça, S., César, J., Neves, L., 2005. Carbono orgânico e estabilidade de agregados de um Latossolo Vermelho sob diferentes manejos. Pesqui Agropecu Bras 40, 487–494.

Xia, Q., Rufty, T., & Shi, W. (2020). Soil microbial diversity and composition: Links to soil texture and associated properties. Soil Biology and Biochemistry, 149. https://doi.org/10.1016/j.soilbio.2020.107953.

Yu, C., Mawodza, T., Atkinson, B. S., Atkinson, J. A., Sturrock, C. J., Whalley, R., Hawkesford, M. J., Cooper, H., Zhang, X., Zhou, H., & Mooney, S. J. (2024). The effects of soil compaction on wheat seedling root growth are specific to soil texture and soil moisture status. Rhizosphere, 29. https://doi.org/10.1016/j.rhisph.2023.100838.

Zhang, R., 1997. Determination of Soil Sorptivity and Hydraulic Conductivity from the Disk Infiltrometer. Soil Science Society of America Journal 61, 1024–1030. https://doi.org/10.2136/sssaj1997.03615995006100040005x.

Zhao, R., Gabriel, J. L., Rodríguez Martín, J. A., Feng, Z., & Wu, K. (2022). Understanding trade-offs and synergies among soil functions to support decision-making for sustainable cultivated land use. Frontiers in Environmental Science, 10. https://doi.org/10.3389/fenvs.2022.1063907.

5 Supplementary material

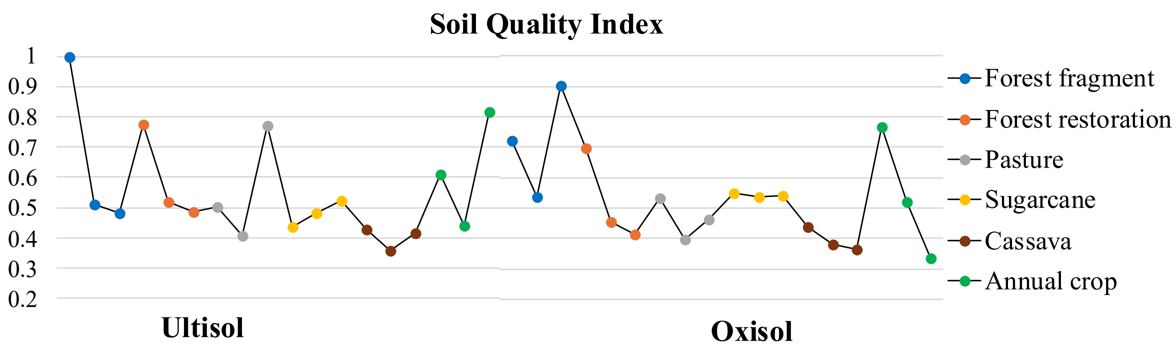


Fig. S 1. Variability between repetitions of the soil quality index in Pontal do Paranapanema-SP.

Table S. 1. Mean comparison test of the attributes used to compose the ecosystem services index.

	Oxisol						Ultisol					
	F. Fragment	F. Restoration	Pasture	Sugarcane	Cassava	Annual crop	F. Fragment	F. Restoration	Pasture	Sugarcane	Cassava	Annual crop
Sand	72.1	85.9	82.3	71.8	82.1	78.3	82.1	79.2	87.2	77.1	87.2	79.5
Silt	6.5	1.7	4.9	4.6	5.5	3.3	1.4	4.0	4.2	4.3	2.1	6.3
Clay	21.4	12.3	12.9	23.6	12.4	18.4	16.6	16.7	8.0	18.6	10.7	14.2
SOC (%)	1.04a	0.46bc	0.85ab	0.59abc	0.47bc	0.51bc	0.60abc	0.86ab	0.54bc	0.67abc	0.27c	0.48bc
C Stock (Mg.ha)	17.83a	12.29a	21.55a	19.83a	11.80a	14.72a	15.37a	20.55a	14.67a	18.68a	8.96a	14.63a
C Particulate (%)	0.47a	0.52a	0.62a	0.29a	0.23a	0.47a	0.33a	0.27a	0.50a	0.32a	0.18a	0.22a
C mineral (%)	1.91a	2.15a	2.48a	1.62a	1.64a	1.76a	2.32a	2.29a	1.91a	1.95a	1.55a	1.90a
C of Microbial Biomass	595.5a	178.6ab	480.9ab	377.1ab	203.6ab	374.1ab	356.1ab	305.2ab	302.6ab	237.7ab	98.6b	181.1ab
Basal respiration	95.73a	80.14a	63.27a	51.69a	60.74a	54.52a	67.64a	95.09a	53.22a	60.36a	46.89a	66.13a
Glucosidase	236.12a	93.97a	123.91a	129.99a	102.19a	194.60a	147.50a	174.78a	98.69a	101.57a	61.92a	100.94a
QCo2	0.16a	0.93a	0.14a	0.16a	0.32a	0.16a	0.27a	0.32a	0.21a	0.51a	0.70a	0.42a
ph	4.87a	4.70a	5.70a	6.13a	5.37a	6.07a	4.97a	4.93a	5.97a	5.67a	5.37a	6.13a
K	7.23a	21.16a	13.71a	8.12a	0.00a	57.43a	41.42a	67.12a	3.75a	8.06a	4.56a	46.55a
P	1.89 to	2.06a	2.53a	34.38a	2.69a	22.96a	1.27a	5.22a	2.30a	15.75a	1.63a	6.57a
Na	2.33a	4.67a	5.00a	6.67a	3.00a	4.67a	2.67a	4.33a	3.00a	3.67a	2.00a	3.33a
Ca	0.81a	0.63a	1.00a	2.49a	1.00a	2.20a	1.40a	1.24a	1.01a	2.08a	0.91a	1.86a
Mg	0.55a	0.40a	0.73a	1.25a	0.48a	0.84a	0.65a	0.84a	0.77a	1.03a	0.66a	0.75a
Al	0.47a	0.30a	0.10a	0.10a	0.10a	0.17a	0.33a	0.17a	0.10a	0.17a	0.10a	0.10a
H+Al	2.83ab	2.13abc	1.80abc	1.10abc	0.93c	1.47abc	2.87a	2.40abc	1.10abc	1.53abc	1.00c	1.07bc
SB	1.38a	1.08a	1.77a	3.77a	1.48a	3.19a	2.07a	2.25a	1.79a	3.13a	1.59a	2.72a
Effective CEC	1.85a	1.38a	1.87a	3.87a	1.58a	3.35a	2.40a	2.42a	1.89a	3.30a	1.69a	2.82a

CEC pH 7	4.22a	3.21a	3.57a	4.87a	2.42a	4.65a	4.93a	4.65a	2.89a	4.67a	2.59a	3.79a
BS	32.48a	33.99a	49.34a	75.69a	60.90a	65.19a	40.58a	48.78a	62.44a	62.90a	60.52a	63.91a
Sat Al	31.05a	22.68a	5.43a	2.87a	6.54a	7.03a	18.82a	6.92 to	5.38a	8.12a	6.29a	5.33a
P-Rem	46.67a	57.00a	52.90a	48.17a	55.63a	53.60a	50.10a	51.90a	59.27a	53.10a	57.97a	52.90a
N (%)	0.22a	0.12abc	0.19ab	0.15abc	0.11bc	0.13abc	0.15abc	0.20ab	0.12abc	0.15abc	0.07c	0.11bc
Bulk density	1.18c	1.52ab	1.52ab	1.75a	1.52ab	1.58ab	1.34bc	1.54ab	1.55ab	1.57ab	1.60ab	1.63ab
GMD	0.92a	0.77a	1.08a	0.66a	0.88a	0.61a	0.77a	0.74a	0.67a	0.51a	0.57a	0.79a
MWD	1.75a	1.51a	1.97a	1.66a	1.70a	1.39a	1.46a	1.67a	1.53a	1.41a	1.31a	1.84a
Infiltration cm/s	1.90a	2.73a	4.30a	4.43a	2.76a	4.33a	1.73a	4.20a	3.90a	5.15a	7.13a	6.50a
Ks	218.3a	181.7a	32.6cd	16.6d	30.4cd	39.2cd	103.2b	64.8bcd	43.2bcd	28.7cd	84.1bc	36.0cd
Microporosity	0.15bc	0.27ab	0.12bc	0.11c	0.15bc	0.11c	0.32a	0.20abc	0.12bc	0.10c	0.21abc	0.22abc
Macroporosity	0.30a	0.12b	0.20ab	0.18ab	0.16ab	0.21ab	0.14ab	0.18ab	0.18ab	0.18ab	0.12b	0.12b
Total porosity	0.46a	0.40ab	0.32ab	0.30b	0.31b	0.32b	0.45a	0.39ab	0.30b	0.27b	0.33ab	0.34ab
SRP	2.15a	3.27a	1.82a	3.04a	2.35a	3.92a	5.42a	1.54a	3.43a	1.87a	1.63a	2.05a

Subtitle: **SOC** = soil organic carbon; **C stock** = stock C**; QCo2** = metabolic quotient**; pH** = active acidity**; k** = potassium; **P** = phosphorus**; Na** = sodium**; Ca** = calcium**; Mg** = magnesium**; Al** = aluminum**; H + Al** = potential acidity; **SB** = sum of bases; **Effective CEC** = cation exchange capacity**; CEC pH 7** = cation exchange capacity in pH 7; **BS** = Base saturation**; P-Rem** = remaining phosphorus; **N** = nitrogen**; MWD** = mean weight diameter; **GMD** = geometric mean diameter**; Ks** = saturated conductivity; **RP** = soil penetration resistance. Note. Means followed by the same letter are not statistically different (p>0.5).

THIRD PARTY

Final Considerations

The results indicate that different land uses promote the accumulation and depletion of SOC differently among soil classes. The gap in SOC stock between the two soil types demonstrates that management practices for each land use must be adapted to specific soil types to optimize carbon sequestration. These steps are crucial for enhancing SOC storage and mitigating the impacts of climate change on tropical sandy soils.

Different land uses significantly influence the soil's ability to provide ecosystem services. Additionally, there are important synergies between ES related to carbon cycling and soil fertility, as well as trade-offs in intensive systems such as pasture and cassava cultivation. The ecosystem services index provides a practical tool to assist in soil management and land use decisions in tropical regions of the Atlantic Forest biome, as it indicates which soil ecosystem services are impaired or improved in each management system, facilitating decision-making aimed at improving production systems.

Microbiological indicators stand out in the evaluation of tropical soils of coarse texture and naturally fragile. Microbial biomass carbon, β-glucosidase, and the metabolic quotient were sensitive tools for identifying the impacts of different soil uses in Ultisols and Oxisols. Canonical correlation analysis reinforced the relationship between microbiological attributes and the physical and chemical quality of the soil, demonstrating the efficiency of these indicators in soil quality evaluation. This study emphasized the interdependence between soil structure and functionality, highlighting the importance of sustainable management practices that preserve organic matter, structure, and biological processes, ensuring the resilience of tropical soils.

REFERENCES

ADEODATO, S. **Quanto Vale?** Capital Natural, Out 2018.

ARMBRUST, D. V. **Soil erosion research methods**. 2nd ed. Ankeny: Soil and Water Conservation Society, 1994.

BARBOSA, L. C. et al. Soil texture affects root penetration in Oxisols under sugarcane in Brazil. **Geoderma Regional**, v. 13, p. 15–25, 2018. DOI: 10.1016/j.geodrs.2018.e00025.

BERNOUX, M. et al. Brazil's soil carbon stocks. **Soil Science Society of America Journal**, v. 66, p. 888–896, 2002. DOI: 10.2136/sssaj2002.8880.

BERTOL, O. J. et al. **Manejo e conservação do solo e da água**. Florianópolis: Epagri, 2016.

BICALHO, I. M. Alteração na agregação e carbono orgânico total em solo cultivado com café sob diferentes sistemas de manejo. **Enciclopédia Biosfera**, Goiânia, v. 7, n. 12, 2011.

BRADY, N. C. and WEIL, R. R. **The nature and properties of soils**. 14th ed. Upper Saddle River: Pearson Education, 2008.

BRASIL. Lei nº 12.651, de 25 de maio de 2012. Dispõe sobre a proteção da vegetação nativa. Disponível em: http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm. Acesso em: 16 abr. 2025.

BRUN, E. J. and CONCEIÇÃO, P. C. Matéria orgânica como indicador da qualidade do solo em florestas plantadas. **Sistemas de Produção Agropecuária**, 2010. Disponível em: https://www.researchgate.net/publication/236144563. Acesso em: 16 abr. 2025.

CARDOSO, A.; POTTER, R. O. and DEDECEK, R. A. Estudo comparativo da degradação de solos pelo uso agrícola no noroeste do Paraná. **Pesquisa Agropecuária**, v. 2, n. 27, 1992.

CARRASCO, R. A. et al. Land use/land cover change dynamics and their effects on land surface temperature in the western region of the state of São Paulo, Brazil. **Regional Environmental Change**, , v. 20, n. 3, p. 96, 2020. DOI: 10.1007/s10113-020-01664-z.

CHERUBIN, M. R. et al. Soil quality indexing strategies for evaluating sugarcane expansion in Brazil. **PLoS ONE**, v. 11, n. 3, e0150860, 2016. DOI: 10.1371/journal.pone.0150860.

DROBNIK, T. et al. Soil quality indicators – From soil functions to ecosystem services. **Ecological Indicators**, v. 94, p. 151–169, 2018. DOI: 10.1016/j.ecolind.2018.06.052.

FELICIANO, C. A. **Violência, desmatamento e luta pela retomada das de terras griladas no Pontal do Paranapanema: da destruição dos territórios indígenas à construção de uma região em disputa de classes**. v. 19, n. 3, Fev 18DC.

FERNANDES, B. M. and RAMALHO, C. B. **Luta pela terra e desenvolvimento rural no Pontal do Paranapanema (SP)**. Estudos Avançados, v. 43, n. 15, 2001.

FERNANDES, B. et al. **Agrofuel policies in Brazil: Paradigmatic and territorial disputes**. Journal of Peasant Studies, v. 37, n. 4, p. 793–819, 2010.

FOLEY, J. A. et al. **Global consequences of land use**. Science, v. 309, n. 5734, p. 570–574, 2005. DOI: 10.1126/science.1111772.

FRANZLUEBBERS, A. J. Soil organic matter stratification ratio as an indicator of soil quality. **Soil and Tillage Research**, v. 66, n. 2, p. 95–106, 2002. DOI: 10.1016/S0167-1987(02)00018-1.

GAZZONI, D. L. **O impacto do uso da terra na sustentabilidade dos biocombustíveis - Documentos 347**. Jan 2014. Disponível em: <www.cnpso.embrapa.br>.

GOUVEIA, V. M. and ANGELO, H. **Economic analysis of carbon fixation and storage in a population of Tectona grandis L.f.** Brasil Florestal, v. 21, n. 74, p. 25–36, 2002. Disponível em: <https://www.cabidigitallibrary.org/doi/full/10.5555/20023191493>.

HAQUE, M. D., et al. **Soil thermal properties: influence of no-till cover crops**. Canadian Journal of Soil Science, v. 104, n. 3, p. 246–256, 1 Set 2024.

HUSSAIN, S. et al. **Carbon sequestration to avoid soil degradation: A review on the role of conservation tillage**. Plants.: MDPI., 1 Out 2021

KROLL, F. et al. **Rural-urban gradient analysis of ecosystem services supply and demand dynamics**. Land Use Policy, v. 29, n. 3, p. 521–535, Jul 2012.

KUMAR, R. **Environment, Farming Systems and Sustainable Agriculture**. Environmental Science Archives, v. 1, 2024. Disponível em: <www.envsciarch.com>.

LAL, R. **Soil carbon sequestration impacts on global climate change and food security**. Science, v. 304, n. 5677, p. 1623–1627, 2004. DOI: 10.1126/science.1097396.

LAL, R.; KIMBLE, J. and FOLLETT, R. F. **Pedospheric processes and the carbon cycle**. Boca Raton: CRC Press, 1997.

LAL, R. **Métodos para a avaliação do uso sustentável dos recursos solo a água nos trópicos**. 3. ed., 1999.

LANA, R. M. Q. et al. **Soil physical attributes and productivity of sugarcane under different cropping systems in the savannah goiano**. Australian Journal of Crop Science | Journal Article, 2017. Disponível em: <https://search.informit.org/doi/epdf/10.3316/informit.821582045447748>.

LANGE, A. et al. **Soil degradation by the extensive livestock in the southern amazon of the state of Mato Grosso**. Nativa, v. 7, n. 6, p. 642–648, 2019.

LOPES, F. B. et al. **Proposta de um índice de sustentabilidade do Perímetro Irrigado Baixo Acaraú, Ceará, Brasil**. Revista Ciencia Agronomica, v. 40, n. 2, p. 185–193, 2009. Disponível em: <http://www.ccarevista.ufc.br/seer/index.php/ccarevista/article/view/510/346>.

MADDEN, J. R. SHIBUSAWA, H. and HIGANO, Y. **Environmental Economics and Computable General Equilibrium Analysis**. 41. ed. Singapore: Springer Singapore, 2020. v. 41. Disponível em: <http://link.springer.com/10.1007/978-981-15-3970-1>. (New Frontiers in Regional Science: Asian Perspectives).

MILNE, E., et al. **Soil carbon, multiple benefits**. Environmental Development, v. 13, p. 33–38, 1 Jan 2015.

OLIVEIRA, F. R. A., VALARINI, P. J. and RONEI J. **Vista do Indicadores de qualidade do solo em área de mata e cultivado com cana orgânica e convencional**. Revista Brasileira de Agroecologia, v. 2, p. 1299–302, Out 2007.

OLIVEIRA, I. N. et al. **Tillage systems impact on soil physical attributes, sugarcane yield and root system propagated by pre-sprouted seedlings**. Soil and Tillage Research, v. 223, 1 Set 2022.

ORIGUÉLA, C. F., FERNANDES, B. M. and FELICIANO, A. F. A atualidade da luta pela terra no Pontal do Paranapanema-SP. Out 2012, Presidente Prudente: Out 2012.

OTTO, R. et al. **Fitomassa de raízes e da parte aérea da cana-de-açúcar relacionada à adubação nitrogenada de plantio**. Pesquisa Agropecuária Brasileira, v. 44, n. 4, p. 398–405, Abr 2009.

PAL, S. and ZIAUL, S. k. **Detection of land use and land cover change and land surface temperature in English Bazar urban centre**. Egyptian Journal of Remote Sensing and Space Science, v. 20, n. 1, p. 125–145, 1 Jun 2017.

PIMENTA, J. P. O. e ROCHA, P. C. **A apropriação do relevo no município de mirante do Paranapanema-SP: lógica de ocupação entre a indústria canavieira e as pequenas propriedades**., Mar 2018.

RABOT, E. et al. **Soil structure as an indicator of soil functions: A review**. Geoderma: Elsevier B.V., 15 Mar 2018

RODRIGUES, M. R. et al. **Avaliação da influência do uso e cobertura da terra na qualidade das águas superficiais da bacia hidrográfica do rio Pirapozinho (SP)**. Revista Brasileira de Geografia Física, v. 12, n. 3, p. 738–753, 2019. Disponível em: <www.ufpe.br/rbgfe>.

ROMAGNOLI, I and MANZIONE, R L. **Mapeamento da vulnerabilidade e riscos de contaminação das águas subterrâneas na região do Pontal do Paranapanema (UGRHI-22)**. Brazilian Journal of Biosystems Engineering v, v. 12, n. 3, p. 307–326, 2018. Disponível em: <http://www.dsr.inpe.br/laf/canasat/>.

ROQUE, P. **O BRASIL NA COP-21**. Out 2015.
SÁ, M. A. C. et al. **Comparação entre métodos para o estudo da estabilidade de agregados em solos**. Pesq. agropec. bras, v. 35, n. 9, p. 1825–1834, Set 2000.

SAIDY, A. R. et al. **The sorption of organic carbon onto differing clay minerals in the presence and absence of hydrous iron oxide**. Geoderma, v. 209–210, p. 15–21, Nov 2013.

SCARPARE, F. V., et al. **Tillage effects on soil physical condition and root growth associated with sugarcane water availability**. Soil and Tillage Research, v. 187, p. 110–118, 1 Abr 2019.

SILVA, A. S. **O caminho da terra: revisitando a história do MST no Pontal do Paranapanema – SP – desde uma ótica psicopolítica**. Psicologia em Estudo, v. 15, n. 1, p. 137–149, Mar 2010.

SILVA, M. S. et al. **Avaliação da cobertura do solo como indicador de gestão de recursos hídricos: Um caso de estudo na sub-bacia do Córrego dos Bois, Minas Gerais**. Engenharia Sanitaria e Ambiental, v. 22, n. 3, p. 445–452, 1 Maio 2017.

SILVA, P. F., et al. **Efeito do desmatamento e do cultivo sobre características físicas e químicas do solo sob floresta natural na Amazônia Oriental**. Revista do Instituto Geológico, v. 11, n. 1, p. 21–33, 1 Jun 1990. Disponível em: <https://revistaig.emnuvens.com.br/rig/article/view/175>.

SILVA-OLAYA, A. M., et al. **Composite index for soil-related ecosystem services assessment: Insights from rainforest-pasture transitions in the Colombian Amazon**. Ecosystem Services, v. 57, 1 Out 2022.

SMITH, P., et al. **The role of soils in delivering Nature's Contributions to People**. Philosophical Transactions of the Royal Society B: Biological Sciences, v. 376, n. 1834, 27 Set 2021.

SOARES, T. O. et al. **Impactos ambientais causados pelo desmatamento: uma revisão sistemática da literatura**. Revista Saúde e Meio Ambiente-RESMA, v. 9, n. 2, p. 66–73, Ago 2019.

SOUZA, G. C. P. **Crescimento econômico, desmatamento e emissões de gases de efeito estufa: análises prospectivas para os biomas brasileiros numa perspectiva de sustentabilidade**. 2022. Universidade Federal de Minas Gerais, 2022.

SPARKS, D. L. Fundamentals of Soil Chemistry. Encyclopedia of Water. : Wiley, 2019. p. 1–11.

SPECHT, A. and WEST, P. W. **Estimation of biomass and sequestered carbon on farm forest plantations in northern New South Wales, Australia**. Biomass and Bioenergy, v. 25, n. 4, p. 363–379, 2003.

STEVENSON, F. J. and COLE, M. A. **Cycles of Soils: Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients**. 2. ed., 1999.

TENELLI, S. et al. **Well-managed grass is a key strategy for carbon storage and stabilization in anthropized Amazon soils**. Journal of Environmental Management, v. 373, 1 Jan 2025.

THAIS F. DA S. VICENTE et al. **Relações de atributos do solo e estabilidade de agregados em canaviais com e sem vinhaça**. Revista Brasileira de Engenharia Agrícola e Ambiental, v. 16, n. 1215–1222, 2012.

THOMAZ J. A. **O agrohidronegócio no centro das disputas territoriais e de classe no Brasil do século XXI**. CAMPO-TERRITÓRIO: revista de geografia agrária, v. 5, n. 10, p. 92–122, Ago 2010.

TOTTI, M. C. V., et al. **Organic carbon stocks across various land use systems in Sandy Ultisols and Oxisols in Brazil**. Geoderma Regional, v. 40, 1 Mar 2025.

VASCONCELOS, R. F. B. et al. **Qualidade física de Latossolo Amarelo de tabuleiros costeiros em diferentes sistemas de manejo da cana-de-açúcar**. v. 18, p. 381–386, Nov 2014. Disponível em: <http://www.agriambi.com.br>.

VENGAVASI, K., et al. **Deficiency, Critical Threshold, and Sufficiency Levels for Hydroponic Supplementation of Major Nutrients for Evaluating Sugarcane under Controlled Conditions**. Journal of Soil Science and Plant Nutrition, v. 24, n. 1, p. 1002–1014, 1 Mar 2024.

VEZZANI, F. M. and MIELNICZUK, J. **Uma visão sobre qualidade do solo**. Revista Brasileira de Ciência do Solo, v. 33, n. 4, p. 743–755, 2009.

WANG, J., WANG, X. and ZHANG, J. Land Use Impacts on Soil Organic and Inorganic Carbon and Their Isotopes in the Yanqi Basin., 2018. p. 69–88.

WINK, C., REINERT, D. J. and MINELLA, J. P. G. **Carbon and nitrogen distribution pattern in soil profile cultivated with Eucalyptus**. Floresta e Ambiente, v. 26, n. 4, 2019.

WORLD RESOURCES INSTITUTE (WRI). **Os países que mais emitiram gases de efeito estufa**, 17 Jun 2024. Disponível em: <https://www.wribrasil.org.br/noticias/os-paises-que-mais-emitiram-gases-de-efeito-estufa>.

ZANELLO, R. and MICHEELS, E. **Beyond the Pasture: A Review of Business Risk and Rangeland Management Decisions**. Rangeland Ecology and Management, v. 98, p. 550–560, 1 Jan 2025.

ZINN, Y. L. et al. **Soil organic carbon retention more affected by altitude than texture in a forested mountain range in Brazil**. Soil Research, v. 56, n. 3, p. 284–295, 2018.

ZINN, Y. L., LAL, R., and RESCK, D. V.S. **Changes in soil organic carbon stocks under agriculture in Brazil**. Soil and Tillage Research, v. 84, n. 1, p. 28–40, Nov 2005a.

ZINN, Y. L., LAL, R. and RESCK, D. V.S. **Texture and organic carbon relations described by a profile pedotransfer function for Brazilian Cerrado soils**. Geoderma, v. 127, n. 1–2, p. 168–173, Jul 2005b.