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BETSY CAROLINA MUÑOZ DE PAEZ

MODELOS DE CAPACIDADE DE SUPORTE DE CARGA NA AVALIAÇÃO DA QUALIDADE ESTRUTURAL DE TECNOSSOLOS E LATOSSOLOS

LAVRAS – MG

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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 obtenção do título de Doutor.

Prof. PhD. Moacir de Souza Dias Junior
Orientador

Prof. Dr. Eduardo da Costa Severiano
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BETSY CAROLINA MUÑOZ DE PAEZ

MODELOS DE CAPACIDADE DE SUPORTE DE CARGA NA EVALUAÇÃO DA QUALIDADE ESTRUTURAL DE TECNOSSOLOS E LATOSSOLOS

BEARING CAPACITY MODELS IN EVALUATING THE SOIL STRUCTURAL QUALITY OF TECHNOSOLS AND OXISOLS

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 obtenção do título de Doutor.

APROVADA em 01 de dezembro de 2023
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A Deus pela sua infinita misericórdia.

Às minhas filhas: Daniela de Jesús e Camila Valentina,

seu amor é a força que me empurra para frente.

A o meu esposo Denny, por me acompanhar em cada desafio.

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RESUMO GERAL

A qualidade estrutural dos solos (QES) é de grande relevância para o crescimento das plantas e a produtividade dos cultivos, pois interfere em processos importantes que determinam um adequado ambiente no solo, determinando a retenção e infiltração da água, trocas gasosas, matéria orgânica do solo e dinâmica de nutrientes, penetração de raízes e suscetibilidade à erosão. Contudo, a qualidade estrutural do solo pode ser facilmente afetada pelas ações do homem que interferem de maneira direta ou indireta sobre o solo. Embora existam diversos indicadores que permitem avaliar a qualidade estrutural do solo, o estudo das pressões de pré-consolidação (PPC) e a elaboração dos modelos de capacidade de suporte de carga (MCSC) tornam-se interessantes pela riqueza dos resultados entregados. Diversas pesquisas ressaltam a sua utilidade quando analisados juntamente com a granulometria, densidade do solo, porosidade total, macro e microporosidade. Os métodos propostos, permitem não só avaliar o estado inicial de um solo, além disso são úteis para comparar diferentes camadas de um mesmo solo, camadas de diferentes solos e o efeito de diferentes manejos sobre o solo ao longo do tempo. Tendo em conta as múltiplas possibilidades de avaliação que estas metodologias oferecem, objetivou-se a sua utilização para avaliar a qualidade estrutural de solos com restrições para o crescimento das plantas. Em um primeiro momento foram elaborados e comparados MCSC de Tecnossolos formados por rejeitos da mineração de ferro advindos do rompimento da Barragem de Fundão (Mariana, MG), nesses solos foi também determinada a densidade do solo (Ds), densidade de partículas (Dp), porosidade total (Pt), microporosidade (Mic), granulometria e matéria orgânica (MO). Nessa pesquisa foi possível constatar que os Tecnossolos formados, exibem grande capacidade de suporte de carga devido às elevadas pressões de pré-consolidação, como resultado do elevado conteúdo de partículas de silte e areia muito fina que determinam o seu adensamento. Assim, a resistência mecânica dos Tecnossolos é muito expressiva, constituindo-se numa limitante para esses solos. No segundo momento, foram avaliados Latossolos sob manejo agrícola de milho silagem. Nesta pesquisa foram avaliadas duas condições de manejo: convencional e em sucessão com soja como alternativa mais sustentável. Inicialmente foram elaborados os MCSC a fim de identificar a condição inicial dos solos e compará-los junto à mata nativa para avaliar a sua degradação inicial. Logo, foi feita a avaliação da compactação dos solos ao longo de dos ciclos de cultura, incorporando nos MCSC os intervalos de confiança e incluindo neles os valores da PPC obtidos nas diferentes avaliações para quantificar a compactação ou recuperação. Os resultados obtidos demonstram que os solos sob sucessão tinham maior capacidade de suporte de carga ao início da pesquisa, contudo esse sistema mostrou-se mais eficiente em incrementar a resistência do solo à compactação, pois ao final da pesquisa apresentou menor porcentagem de amostras compactadas nas duas camadas avaliadas, além de mostrar melhora na Ds, Pt, Mic e MO. Já nos solos sob monocultura não houve mudanças favoráveis nestas propriedades, sendo que Mic se incrementou junto à diminuição da Mac.

Palavras-chave: Compactação do solo. Adensamento do solo. Milho para silagem. Tecnossolos. Pressoes de pré-consolidação. Modelos de capacidade de suporte de carga.

GENERAL ABSTRACT

A structural quality of soils (SQS) is crucial for plant growth and crop productivity as it impacts essential processes that determine a suitable soil environment, including water retention, gas exchange, soil organic matter, nutrient dynamics, root penetration, and susceptibility to erosion. Human actions can easily affect the structural quality of the soil, directly or indirectly. While there are several indicators for assessing the structural quality of the soil, the study of pre-consolidation pressures (PCP) and the development of load-bearing capacity models (LBCM) are particularly interesting due to the richness of the results they provide. Various research studies emphasize their utility when analyzed alongside particle size distribution, soil density, total porosity, macro- and microporosity. These methods not only allow for evaluating the initial state of a soil but also prove useful for comparing different layers of the same soil, layers of different soils, and the effect of different soil management practices over time. Considering the multiple assessment possibilities these methodologies offer, their use was aimed at evaluating the structural quality of soils with limitations for plant growth. Initially, load-bearing capacity models (LBCM) were developed and compared for Technosols formed by iron mining tailing resulting from the rupture of the Fundão Dam (Mariana, MG). In these soils, soil density (Ds), particle density (Dp), total porosity (Pt), microporosity (Mic), particle size distribution, and organic matter (OM) were also determined. This research revealed that the formed Technosols exhibit high load-bearing capacity due to high pre-consolidation pressures, a result of the high content of silt and very fine sand particles that determine their compaction. Thus, the mechanical resistance of Technosols is quite significant, posing a limitation for these soils. In the second stage, Oxisols under corn silage agricultural management were evaluated. Two management conditions were assessed: conventional and in succession with soybeans as a more sustainable alternative. Initially, load-bearing capacity models (LBCM) were developed to identify the initial condition of the soils and compare them with native forest to evaluate their initial degradation. Subsequently, soil compaction was assessed over the crop cycles, incorporating confidence intervals into the LBCM and including the PCP values obtained in the different assessments to quantify compaction or recovery. The results demonstrate that the soils under succession had a greater load-bearing capacity at the beginning of the research. However, this system proved to be more efficient in increasing soil resistance to compaction since, at the end of the study, it showed a lower percentage of compacted samples in the two evaluated layers, as well as improvements in Ds, Pt, Mic, and OM. In soils under monoculture, there were no favorable changes in these properties, with an increase in Mic alongside a decrease in Mac.

Keywords: Soil compaction. Soil densification. Silage corn. Technosols. Pre-consolidation pressure. Load-bearing capacity models.

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SUMMARY

PRIMEIRA PARTE: INTRODUÇÃO

INTRODUÇÃO

A qualidade estrutural do solo faz parte de sua qualidade física, e refere-se ao arranjo das partículas do solo constituindo um ambiente dinâmico, cuja alteração determinará um novo comportamento dos processos que ocorrem no solo (FERREIRA, 2010). O anterior determina a importância da qualidade estrutural do solo para o crescimento das plantas, pois condiciona a penetração das raízes, a quantidade de água disponível e outras propriedades e processos importantes do solo, interferindo desta ‘forma na capacidade produtiva e na sustentabilidade ambiental (CAVALIERI-POLIZELI *et al.*, 2022; DEMETRIO *et al.*, 2022; LIMA *et al.*, 2012).

A estrutura do solo expressa claramente os efeitos do manejo adotado, cujas ações de origem física, química e biológica afetam o processo dinâmico de construção ou degradação do solo, que por sua vez afeta o habitat dos microrganismos que regulam a decomposição da matéria orgânica e os ciclos biogeoquímicos, tendo efeito direto na fertilidade do solo e na nutrição das plantas (CUI; HOLDEN, 2015; RABOT *et al.*, 2018; SILVA *et al.*, 2018; STEFANOSKI *et al.*, 2013).

A degradação estrutural do solo tornou-se muito comum pelo excesso de cargas mecânicas aplicadas aos solos, que podem dar lugar à sua compactação, que um processo de perda da qualidade estrutural (BATEY; MCKENZIE, 2006; SCHJØNNING *et al.*, 2015), produzida pelo deterioro das propriedades físicas do solo. Outra causa de degradação estrutural pode ser o adensamento do solo, que ocorre de forma natural pelo processo de pedogênese em rejeitos produzidos pelas atividades de mineração (COURTNEY; HARRINGTON; BYRNE, 2013; PARADELO; MOLDES; BARRAL, 2008; SILVA *et al.*, 2006b). Estes materiais carecem da estrutura com elevado grau de agregação que é típica dos solos naturais e influencia decisivamente muitas das suas propriedades; entre elas estão as propriedades mecânicas do solo (PARADELO; BARRAL, 2013), impondo estrutura mais restritiva aos solos formados.

Isso pode acontecer pelo predomínio de partículas de silte ou areia fina, que geram uma estrutura de maior densidade ao entupir os poros de maior tamanho, dando lugar à preponderância de pequenos poros no solo, conforme relatado por Ribeiro et al. (2007). De acordo com IUSS Working Group WRB (2015) na World Reference Base for Soil Resources 2014, os solos em formação desenvolvidos sobre estes materiais são comumente referidos como Tecnossolos, e de acordo com Dollhopf and Postle (1988) a compactação desses rejeitos é muitas vezes um problema para o estabelecimento de plantas mais grave do que limitações químicas, tais como fertilidade reduzida ou toxicidade potencial.

Dadas as consequências da degradação estrutural dos solos tanto para a produção de alimentos quanto para a o ambiente, é necessário monitorar a sua qualidade por médio de indicadores apropriados. Neste sentido, Cherubin et al. (2016) afirma que esses indicadores devem cumprir quatro funções físicas críticas do solo: apoiar o crescimento das raízes, fornecer água para plantas e organismos edáficos, permitir trocas gasosas entre solo e atmosfera e capacidade de resistir à erosão e à degradação do solo. Essas funções são essenciais para manter a produtividade das culturas e os serviços ecossistêmicos.

Neste sentido, os indicadores que descrevem e quantificam a resistência mecânica, deformação e resiliência de solos agrícolas são importantes por várias razões. Uma delas é avaliar se as cargas mecânicas externas aplicadas aos solos durante as operações de campo modificam as arquiteturas sólido-vazio, e as relações de volume por meio de realocações de partículas e até que ponto isso pode afetar negativamente as funções dos poros (HORN; PETH, 2011).

Portanto, considera-se que entre os atributos físicos capazes de cumprir as funções mencionadas como indicadores da qualidade estrutural do solo estão: densidade do solo, porosidade total, macroporosidade, microporosidade e pressão de pré-consolidação (DA SILVEIRA JUNIOR *et al.*, 2012; KARLEN, 2004; LIN; VAN DER BOLT; CORNELIS, 2022; MARTINS *et al.*, 2018; MOREIRA *et al.*, 2012; OLIVEIRA *et al.*, 2003; PEIXOTO *et al.*, 2019; SCHJØNNING *et al.*, 2015; SEVERIANO *et al.*, 2009; TASSINARI, 2015).

A densidade do solo, também denominada de densidade aparente ou densidade global, expressa a relação entre a massa seca das partículas do solo e o seu volume total, é um atributo físico do solo que reflete o arranjamento das suas partículas, que por sua vez determina as características do espaço poroso (ANDRADE, 2019; CARDOSO *et al.*, 2013; FERREIRA, 2010). Além disso, a densidade do solo depende das condições estruturais e do estado de compactação do solo, estando diretamente relacionada às alterações na estrutura do solo decorrentes do tráfego de máquinas agrícolas (JORGE *et al.*, 2012; KARLEN, 2004; LIMA *et al.*, 2013).

Por outro lado, a avaliação do espaço poroso de solo é muito importante porque interfere na aeração, condução e retenção de água, resistência à penetração e, consequentemente, na nutrição da planta. (WENDLING *et al.*, 2012). Neste sentido, diversos autores referem que a distribuição de poros por tamanho é mais importante do que a porosidade total, porque um solo com boa distribuição de poros, com diâmetros variados, potencializa a atividade agrícola tornando-a mais sustentável. (ANDRADE, 2019; JORGE *et al.*, 2012; WENDLING *et al.*, 2012).

O comportamento compressivo do solo e suas pressões de pré-consolidação estão relacionadas com alterações estruturais do solo produzidas pela compactação (NUNES *et al.*, 2019; SCHJØNNING *et al.*, 2016), por tanto, o seu conhecimento é uma ferramenta importante para a prevenção (IMHOFF *et al.*, 2016; KELLER *et al.*, 2013; LEBERT; BÖKEN; GLANTE, 2007). Neste sentido, a pressão de pré-consolidação é um parâmetro obtido a partir da curva de compressão do solo e tem sido utilizada como um indicador da capacidade de carga do solo, bem como para caracterizar os impactos sofridos pelo uso de máquinas. (SILVA; LIMA, 2015).

A pressão de pré – consolidação e é a única propriedade capaz de estimar os níveis de pressão potencialmente aplicáveis ao solo que poderiam impedir a compactação adicional (MARTINS *et al.*, 2013), e é uma medida da capacidade de suporte de carga do solo, definida como a capacidade da estrutura do solo em resistir a tensões induzidas, sem mudanças irreversíveis no arranjo tridimensional das partículas constituintes do solo (ALAKUKKU *et al.*, 2003; TASSINARI, 2019). Esse propriedade pode ser avaliada pelo ensaio de compressão uniaxial, que é uma medida da resistência mecânica do solo que permite obter as curvas de compressão do solo para quantificar as reduções do seu volume e, portanto, estimar sua suscetibilidade à compactação (DIAS JUNIOR; TASSINARI; MARTINS, 2019)

Por outro lado, em função da variação da pressão de pré-consolidação com a umidade do solo é possível elaborar os modelos de capacidade de suporte de carga. Estes são obtidos representado no eixo das abscissas as umidades volumétricas ou sucções, versus as pressões de pré-consolidação (σp) no eixo das ordenadas (DIAS JUNIOR *et al.*, 2005; OLIVEIRA *et al.*, 2003). Diversos estudos têm sido feitos visando comparar os solos em função dos seus modelos de capacidade de suporte de carga (SILVA et al., 2006; DIAS JUNIOR et al., 2007; SEVERIANO et al., 2009; SILVA; LIMA, 2015; TASSINARI, 2015; MARTINS et al., 2018; SILVA, 2018; ANDRADE, 2019). Estes estudos incluem a avaliação de solos sob manejo agrícola, pecuário, florestal e solos originados de rejeitos da mineração.

Do mesmo modo os modelos de capacidade de suporte de carga têm sido utilizados como ferramenta para avaliar a compactação do solo ou a sua recuperação natural, partindo de uma condição inicial e avaliando o efeito das pressões aplicadas ao solo pelos maquinários ao longo do tempo (KARLEN, 2004; DIAS JUNIOR et al., 2005, 2007; SILVA et al., 2006; SEVERIANO et al., 2010; MARTINS et al., 2013).

Essas pesquisas demonstram a importância e utilidade dos modelos de capacidade de suporte de carga na avaliação da qualidade estrutural dos solos, pois eles oferecem informações que permitem não só avaliar e comparar a qualidade dos solos em função das deformações sofridas em um momento específico, além disso, é possível fazer uma avaliação no tempo que permite identificar o incremento da compactação ou o efeito da recuperação natural ou de práticas de recuperação sobre os solos compactados (DIAS JUNIOR; TASSINARI; MARTINS, 2019).

- Hipóteses, objetivos e estrutura da tese

Baseado no anterior, nesta tese objetiva-se utilizar as pressões de pré–consolidação e os modelos de capacidade de suporte de carga como ferramenta para avaliar a qualidade estrutural de solos, a fim de demostrar a utilidade destas metodologias na avaliação de solos originados sob condições completamente diferentes. Assim, é proposto avaliar solos sob duas condições específicas: a) Tecnossolos formados a partir do rejeito depositado pela ruptura da Barragem de Fundão em Mariana, MG; b) Latossolos sob manejo de milho silagem.

Na avaliação da qualidade estrutural dos Tecnossolos formados a partir de rejeitos de mineração de ferro, se estabeleceram os seguintes objetivos específicos: i) Verificar a capacidade de suporte de carga dos Tecnossolos formados a partir do rejeito produto da mineração e ii) Comparar a capacidade de suporte de carga dos Tecnossolos formados e relacionar com outras propriedades do solo. Para estes objetivos as hipóteses foram: i) Os Tecnossolos terão pressões de pré–consolidação maiores que os solos das áreas não atingidas pelo rompimento das barragens; ii) Nos MCSC os Tecnossolos mostrarão a capacidade de suportar maiores pressões externas, como consequência da sua pedogênese.

Por outro lado, os solos sob manejo de milho silagem foram avaliados a fim de alcançar os seguintes objetivos específicos: i) Propor modelos de capacidade de suporte de carga dos solos sob diferentes manejos de milho para silagem; ii) Avaliar a condição inicial dos solos osb milho silagem através da comparação dos MCSC; e iii) Identificar a variação espaço–temporal da compactação dos solos provocadas pelas operações mecanizadas e a sua recuperação, nos sistemas de manejo avaliados. As hipóteses elaboradas foram três: i) A CSC dos solos será maior nos solos sob manejo agrícola, ii) A compactação dos solos sob milho silagem diferira em função dos manejos adotados; iii) os solos com uso mais intensivo de maquinários apresentarão incremento na porcentagem de amostras compactadas, enquanto mudanças no uso mostraram reflexos de recuperação da qualidade estrutural.

Atendendo aos objetivos, essa tese foi estruturada em dois artigos de pesquisa. No primeiro artigo, foi avaliada a qualidade física dos Tecnossolos formados pela deposição de rejeitos advindos da Barragem de Fundão, baseado na avaliação das suas propriedades físicas e os seus MSCS. Já no segundo artigo foram avaliados solos agrícolas sob manejo de milho para silagem, sobre duas condições

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SEGUNDA PARTE: ARTIGOS

ARTIGO 1. LIMITING PHYSICAL PROPERTIES OF TECHNOSOLS FORMED BY THE FUNDÃO DAM FAILURE, MG, BRAZIL.

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LIMITING PHYSICAL PROPERTIES OF TECHNOSOLS FORMED BY THE FUNDÃO DAM FAILURE, MG, BRAZIL.

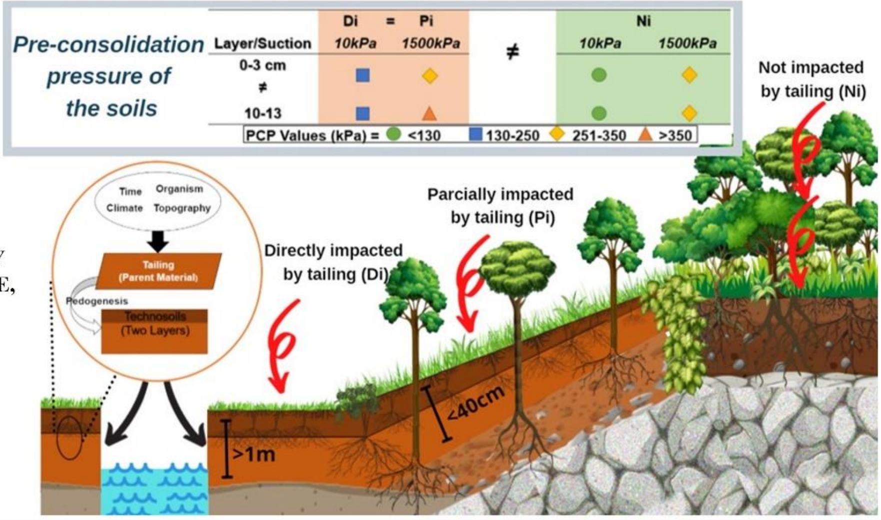
ABSTRACT

The physical properties of the Technosols formed by the deposition of tailings may constitute a physical barrier that limits water movement and plant development due to the properties received from those sediments. This study aimed to evaluate the physical quality of the Technosols formed by the deposition of sediments displaced by the Fundão Dam failure, Mariana, MG, Brazil, based on the evaluation of physical properties and Load Bearing Capacity Models (LBCM). For that, three areas under different types of vegetation were selected: eucalyptus (Euc), forest with human-assisted revegetation (RF), and forest with native vegetation (NF). Three sampling subareas were demarcated in each area: non-impacted areas (Ni), and Technosols formed in directly impacted areas (Di), and partially impacted areas (Pi). Undisturbed samples were collected in two layers and subjected to the uniaxial compression test after they were equilibrated at five matric potentials. Soil compression curves and LBCM were determinated. Soil bulk density (BD), total porosity (TP), organic matter (OM), granulometry, and particle density (PD) were also determined. The results showed that the clay content was less significantly, and the silt and very fine sand content was higher significantly in the Technosols, generating an increase in BD and reduction in TP. Technosols generally exhibited greater load-bearing capacity, due to higher pre-consolidation pressure values attained by these soils, as a result of the lower clay and OM contents. The high resistance of these soils is one limitation for revegetation of the areas evaluated, being necessary use of management practices that promote improvement in the physical properties of the Technosols.

Keywords: tailings deposition, soil physical quality, load-bearing capacity models, pre-consolidation pressures, Technosols

GRAPHICAL ABSTRACT

LIMITING PHYSICAL PROPERTIES OF TECHNOSOLS FORMED BY THE FUNDÃO DAM FAILURE, MG, BRAZIL



Pre-consolidation pressure of the soils

Layer/Suction	Di 10kPa	= Pi 1500kPa	≠	Ni 10kPa	Ni 1500kPa
0-3 cm	■	◆		●	◆
≠					
10-13	■	▲		●	◆

PCP Values (kPa) = ● <130 ■ 130-250 ◆ 251-350 ▲ >350

1. INTRODUCTION

Mining activity is highly technified and generates wealth for a country. However, in spite of all the technology involved, the environmental impact from rupture of tailings retention structures lead to enormous environmental and social damage to the population, as occurred in Mariana (2015) and Brumadinho (2019) in Minas Gerais, Brazil (Schaefer et al., 2016; Carmo et al., 2017; Armstrong et al., 2019).

In Mariana (MG), the tailings led to considerable environmental damage that involved displacement of 50 million m^3 of sediments, affecting not only the waters of the Doce River, but also around 457.6 ha of forest (Marta-Almeida et al., 2016; Omachi et al., 2018). Permanent deposition of tailings of variable depth on the soils in native ecosystems and systems under agricultural production produced environmental damage, as well as associated economic and social damage.

The deposition of tailings along the edges of the Doce River basin, the thickness of these tailings, and the impossibility of removing them are sufficient indicators to classify the soils under study as Technosols (Huot et al., 2012, 2015; Asensio et al., 2013), a concept introduced in 2006 by the World Reference Base for Soil Resources (WRB-FAO) (IUSS Working Group WRB., 2006). According to this classification system, Technosols are soils constituted in the upper 100 cm by 20 percent or more (in volume) of material of human origin, whose properties and pedogenesis are dominated by their technical origin.

In a similar manner, in 2001, discussions began regarding the need to consider the limitations of the Soil Taxonomy classification system for classifying soils impacted by human activity, producing revision and modification of the system in 2014 (Soil Survey Staff, 2014) to thus ensure adequate classification and survey of soils altered and transported by humans (Wilding and Ahrens, 2002; Echevarria and Morel, 2015).

Technosols are found worldwide where human activities have led to the formation of artificial soils, the sealing of original soils, or the extraction of materials (ISRIC, 2023). They are generically defined as soils with indications of pedogenetic development, whose properties and functions were defined by human action (Séré et al., 2010; Oliveira Filho and Pereira, 2023). These soils are characteristic soils of urban, industrial, traffic, mining, and military areas (Leguédois et al., 2016). Thus, mining generates large surfaces of degraded Technosols with an annual production of soil material of about 21 Gt.yr-1 (Hayes et al., 2014; Leguédois et al., 2015).

Although the information available on this Technosoils is scarce and recent, interest in monitoring and evaluation has grown. Studies have shown that the properties of this Technosol formed by tailings deposition are completely different from original soils in their physical, chemical, and biological properties (Schaefer et al., 2015; Guerra et al., 2017; Batista et al., 2020; Couto et al., 2021) limiting the adoption of soil use and management practices.

In relation to soil physical properties, the behavior of these waste materials is quite different from those of conventional soils (Radhika et al., 2020). Some studies have indicated the predominance of sand and silt fractions in the tailings (Silva et al., 2006; da Silva et al., 2015). This can cause a physical barrier that limits water movement and the capacity for plant development. Therefore, it is extremely necessary to evaluate soil physical quality, which will contribute to an understanding of the processes involved (Stefanoski et al., 2013; Rabot et al., 2018).

Physical parameters used to evaluate soil physical quality include load-bearing capacity, analyzed by models (Karlen, 2004; Kondo and Dias Junior, 2014). Load-bearing capacity is defined as the capacity of the soil structure to resist induced stresses without irreversible changes in the three-dimensional arrangement of the constituent soil particles (Alakukku et al., 2003; Tassinari et al., 2021).

Therefore, the aim of the present study was to create and compare load-bearing capacity models for Technosols formed by the deposition of iron mine tailings coming from the Fundão Dam seeking to identify the most restrictive conditions for plant development in accordance with soil use, the impact level of the tailings, and the soil layer. Our hypothesis is that the Technosols formed from the tailings will have greater physical restrictions than original soils.

2. MATERIALS AND METHODS

The study area is located in the southeast Brazil, in the state of Minas Gerais (Figure 1A), specifically in the municipality of Mariana (Figure 1B), in the soils affected by the rupture of the Fundão dam located along the banks of the Gualaxo do Norte River nearly four years after deposition of the tailings, three types of areas reflecting diverse vegetation (Figure 1C and 1D), considering their distance from the dam and, consequently, the displacement of the tailings, were chosen for study: an area of planted eucalyptus with human-assisted revegetation (Euc) located 25km from the dam by the river channel; an area of forest with human-assisted revegetation through sowing of herbaceous plants (RF)

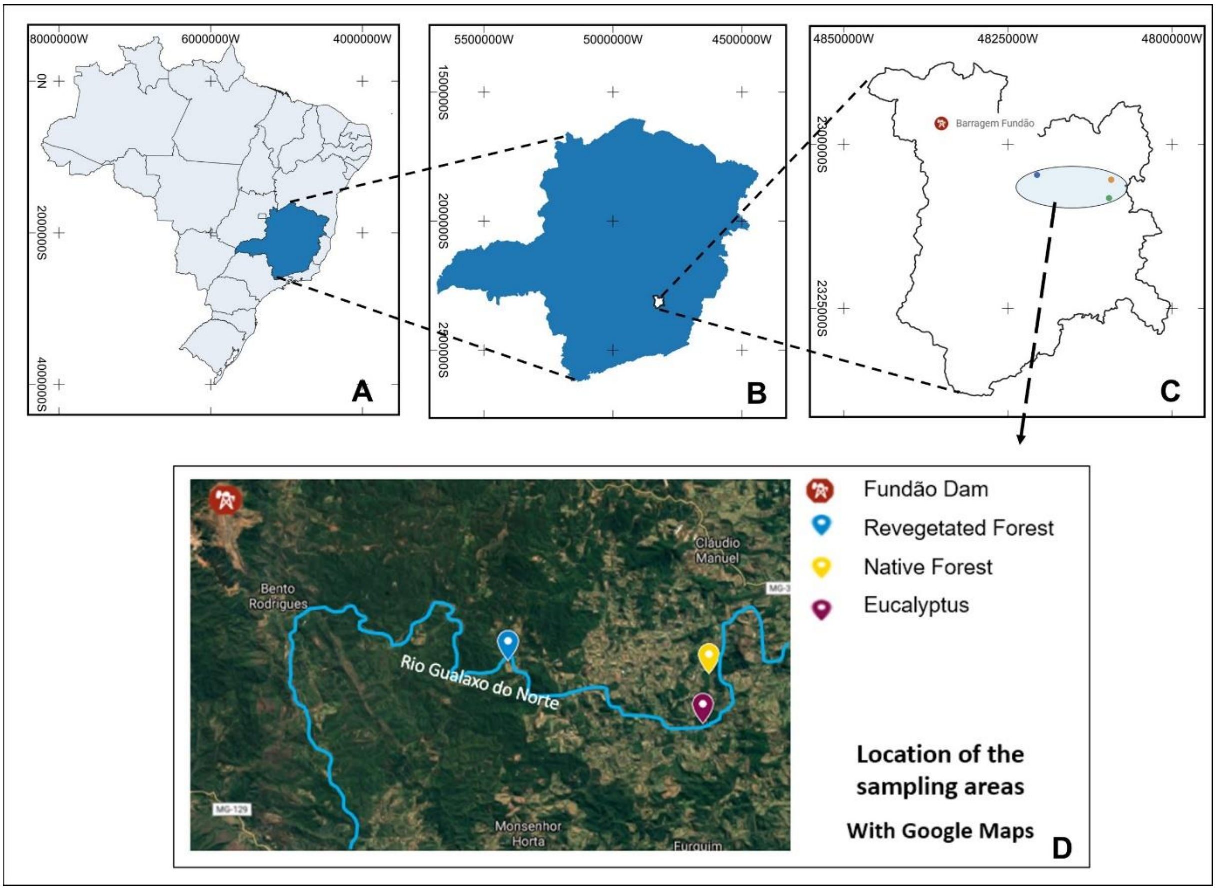


Figure 1. Location of the areas of interest. 1A) state of Minas Gerais (MG), 1B) municipality of Mariana, 1C) area under study, 1D) sampling areas and their location in relation to the Fundão Dam

located 38km from the dam; and an area of forest with native vegetation (NF) whose tailings moved 43km downstream (Figure 1D).

In each type of vegetation, three sampling areas with different levels of impact were demarcated: areas not impacted or without tailings located at the top of the landscape (Ni); and two areas with Technosols: areas partially impacted (Pi) by the rupture of the Fundão Dam, with deposition of tailings up to 40 cm in depth, located on the slope; and areas with deposition of tailings up to 1 m depth, or directly impacted areas (Di), located at the bottom. The location of these areas in the landscape is shown in Figure 2.

In each sampling area, 5 points were selected at random for collection of undisturbed samples in two layers: 0-3 cm and 10-13 cm. The 0-3 cm layer was chosen as the layer most subject to changes by biological activities, and the 10-13 cm layer was chosen as representing greater mechanical resistance in field analyses, which may limit root system development.

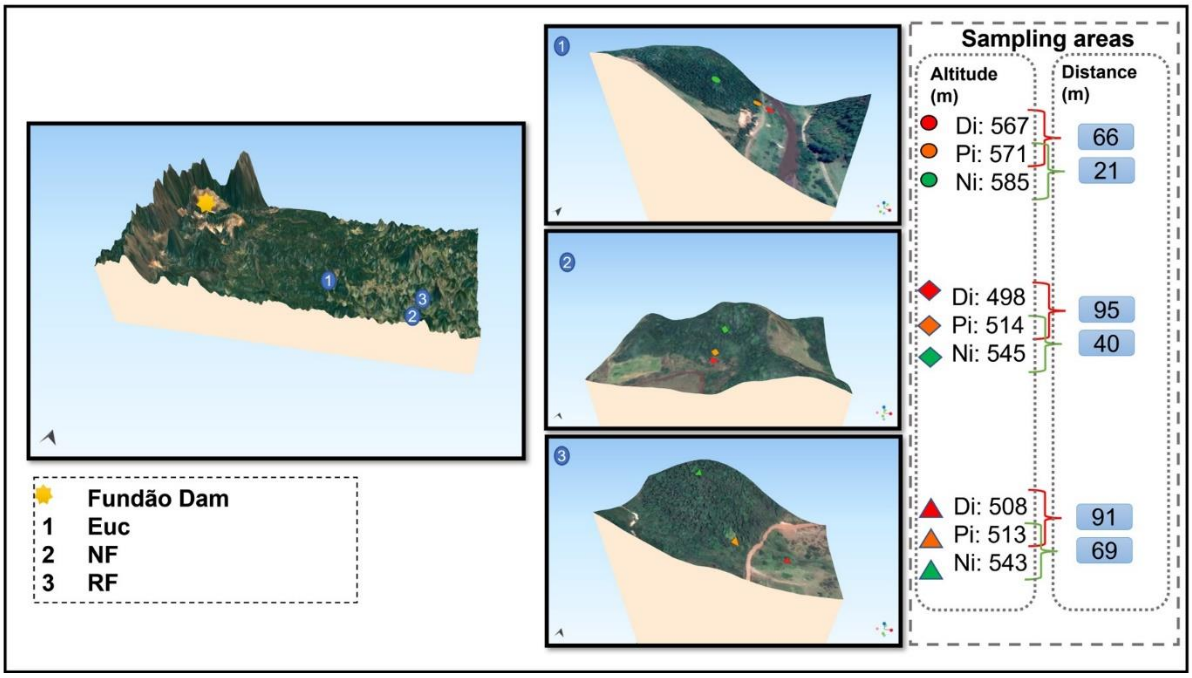


Figure 2. Elevation maps indicating the location of the three types of vegetation (1. Euc: eucalyptus; 2. NF: native forest; 3. RF: revegetated forest), the sampling areas with different impact levels (Di: directly impacted, Pi: partially impacted, and Ni: not impacted), distance between them, and their altitude.

Undisturbed samples were taken using an Uhland sampler with 6.4 cm diameter and 2.5 cm height rings. The samples were wrapped in plastic film and treated with paraffin wax to preserve their structure. These undisturbed samples were initially prepared by removing excess soil from the cylinders, saturated by capillarity, and placed in a Richards extractor, where they drained under the potentials (ψ) -10, -33, -100, -500, and -1500 kPa, and their weight was determined after equilibrium at each potential (Klute, 1986). After that, these samples were subjected to the uniaxial compression test (Dias Junior and Martins, 2017), with application of pressure through use of compressed air. The pressures applied to the samples were 25, 50, 100, 200, 400, 800, and 1600 kPa. Each pressure was applied until 90% of maximum deformation was achieved. Soil compression curves were created with these data, where the preconsolidation pressures (σp) were determined. To obtain the load-bearing capacity models, the potentials were represented on the abscissa (x) axis, and the pre consolidation pressures (σp) were represented on the ordinate (y) axis (Dias Junior et al., 2005) using the Sigma Plot 14 software. These points were fitted to a regression of the $\sigma p = a\Psi m^{b}$ type, where σp is the preconsolidation pressure, Ψm is the matrix potential, and the a and b parameters represent the empirical parameters obtained from fitting the model (Severiano et al., 2013). The regressions were fitted through the R software, version 4.0.3 (R Core Team, 2020), which was applied to the models of pre consolidation pressure of the soil samples. The estimated soil equations were statistically compared using the Snedecor and Cochran

(1989) test for linear models, which includes a data homogeneity test (F test), the angular coefficient (b), and the significance of the linear coefficient (a) of the equation.

After the tests were performed, the samples were dried in a laboratory oven at 105 °C for 24 h for determination of soil bulk density (BD) (Almeida et al., 2017). Total porosity (TP) was determined by the expression: TP = (1-BD/PD) where BD is soil bulk density and PD is particle density (Viana et al., 2017).

The excess of material removed from the rings was used as disturbed samples. They were dried in air, passed through a 2.0 mm sieve, and used in the following analyses: organic matter (OM) (Cantarella et al., 2001); granulometry by the pipette method, with fractionation of sand to determine the very fine (VF), fine, media, coarse, and very coarse sand fractions (Donagemma et al., 2017); and particle density by the volumetric flask method (Viana et al., 2017).

A completely randomized experimental design was set up to statistically analyze the results to BD, PD, TP, clay, silt, sand, and sand fractions. Before proceeding with the analysis, a transformation that maximizes the likelihood of the normal model was selected for each variable (Box and Cox, 1982). On the other hand, when factors and/or interactions were detected with significant effects in ANOVA, comparisons of means were conducted using the Scott-Knott test ($p < 0.01$).

3. RESULTS

3.1. Characterization and physical properties of the soils

The soils under study belong, in general, to the medium texture group, but the original soils are classified in the sandy clay loam texture, while the Technosols range from loam to sandy loam texture.

The results obtained for particle size distribution in the soils studied is shown in Figure 3. The soils are clustered according to the results of the Scott-Knott test ($p < 0.01$) and classified in an ascending manner. The soils with the highest values for each trait or property are always in the first groups. Thus, the clay contents were highly variable, generating seven groups (Fig. 3a). For this trait, the lowest values correspond to Di and Pi (clustered in “d”, “e”, “f” and “g”) with clay from 45 to 105 g kg^{-1}. These soils also obtained the highest values for silt (419-480 g kg^{-1}) grouped in “a”, in contrast with the Ni soils (“b” and “c” groups), which had silt from 165 to 280 g kg^{-1} (Figure 3b).

In contrast, the soils were separated into only two groups regarding the total sand content, with impacted and non-impacted soils in both groups (Fig. 3c). In addition, the results for very fine sand (VFS) are similar to those of silt (Figure 3d). For the Ni soils, the values ranged from 33 to 65 g kg^{-1} (group “c”), whereas for the Technosols, the values were from 189 to 279 g kg^{-1} (groups “a” and “b”) exhibiting significantly higher values.

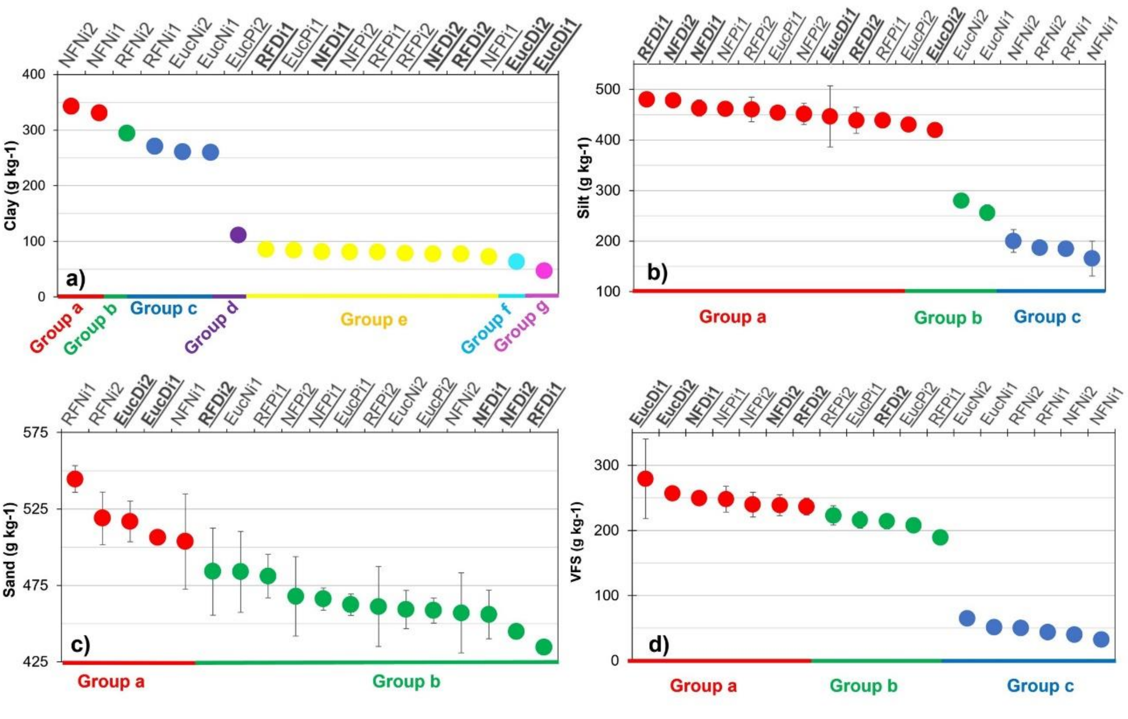


Figure 3. Content of a) clay, b) silt, c) total sand, and d) very fine sand (VFS), clustered by the Scott-Knott test at 1%, in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). Layers evaluated: 1 (surface layer – 0-3 cm), 2 (subsurface layer – 10-13 cm).

The PD (Figure 4) were highly variable in the soils studied, generating seven groups. In the first five are the areas under the Technosols (Di and Pi), which have PD from 2.78 to 2.94 Mg m^{-3}, compared to the Ni soils, which had PD from 2.40 to 2.60 Mg m^{-3}. The highest PD corresponded to the soils under RF, with PD of 2.94 Mg m^{-3} in the two layers evaluated. On the other hand, soil bulk density (BD) in the 18 conditions analyzed exhibited four homogeneous groups (Figure 5a), with the highest BD corresponding to the Technosols, with values from 1.59 to 1.88 Mg m^{-3} (clustered in “a” and “b”). Regarding total porosity (TP), the soils were clustered in 3 homogeneous groups; in this case, the Technosols were clustered in “b” and “c”, with TP from 0.33 to 0.43 m^{3} m^{-3}, significantly lower than in original soils (Figure 5b).

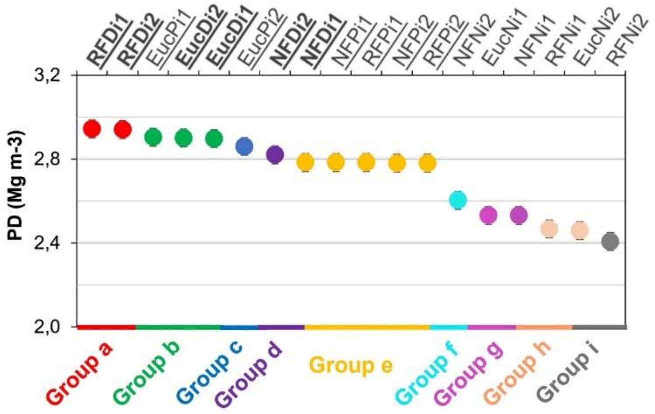


Figure 4. Particle density (PD), clustered by the Scott-Knott test at 1%, in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). Layers evaluated: 1 (surface layer – 0-3 cm), 2 (subsurface layer – 10-13 cm)

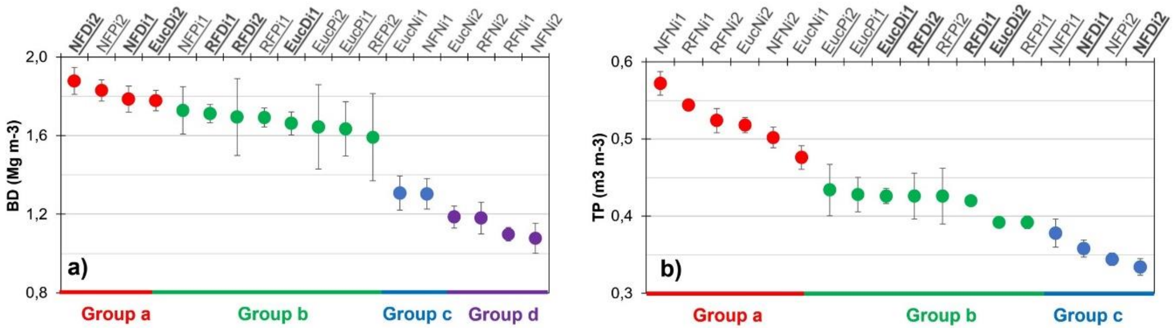


Figure 5. a) soil bulk density (BD) and b) total porosity (TP), clustered by the Scott-Knott test at 1%, in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). Layers evaluated: 1 (surface layer – 0-3 cm), 2 (subsurface layer – 10-13 cm)

In the case of OM, the results obtained show highly variable in the soils under study, giving rise to eight groups (Figure 6). In general, the OM were greater in the soils without tailings and clustered in “a”, “b”, “c”, “d”, and “e” (12.3 to 26.3 g kg^{-1}). In Di and Pi, OM was 2.7 to 8.9 g kg^{-1}. Thus, in Ni in the three vegetations evaluated, the OM values were higher in the surface layer than in the subsurface layer in the following sequence: NF > Euc > RF, with values from 17.8 to 26 g kg^{-1} in the surface layer and from 12.3 to 19.5 g kg^{-1} in the subsurface layer. The Technosols showed the same trend, except for RFPi, which had higher OM contents in the subsurface layer. In Pi and Di, the OM values were variable both in the uses and in the layers evaluated, with values from 2.7 to 8.9 g kg^{-1}.

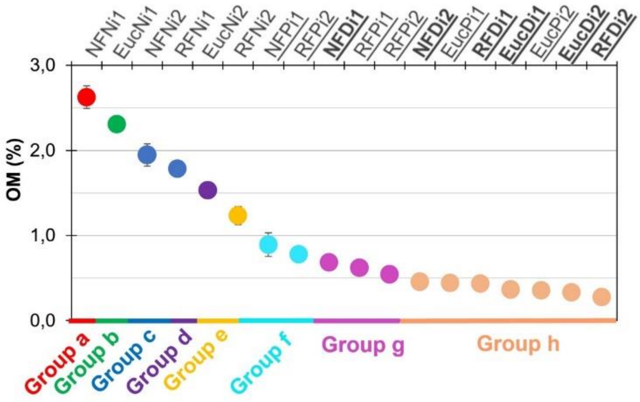


Figure 6. Soil organic matter (OM), clustered by the Scott-Knott test at 1%, in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). Layers evaluated: 1 (surface layer – 0-3 cm), 2 (subsurface layer – 10-13 cm).

The results of correlation between clay content and BD, PD, TP, and OM are shown In Figure 7. For all the traits evaluated, the clay content played a fundamental role in their clustering or segregation. Thus, Ni have the greatest clay contents, with less restrictive or limiting values for the parameters evaluated, whereas in the soils with lower clay contents (Technosols), the properties evaluated were impacted, generating more restrictive or limiting values for them.

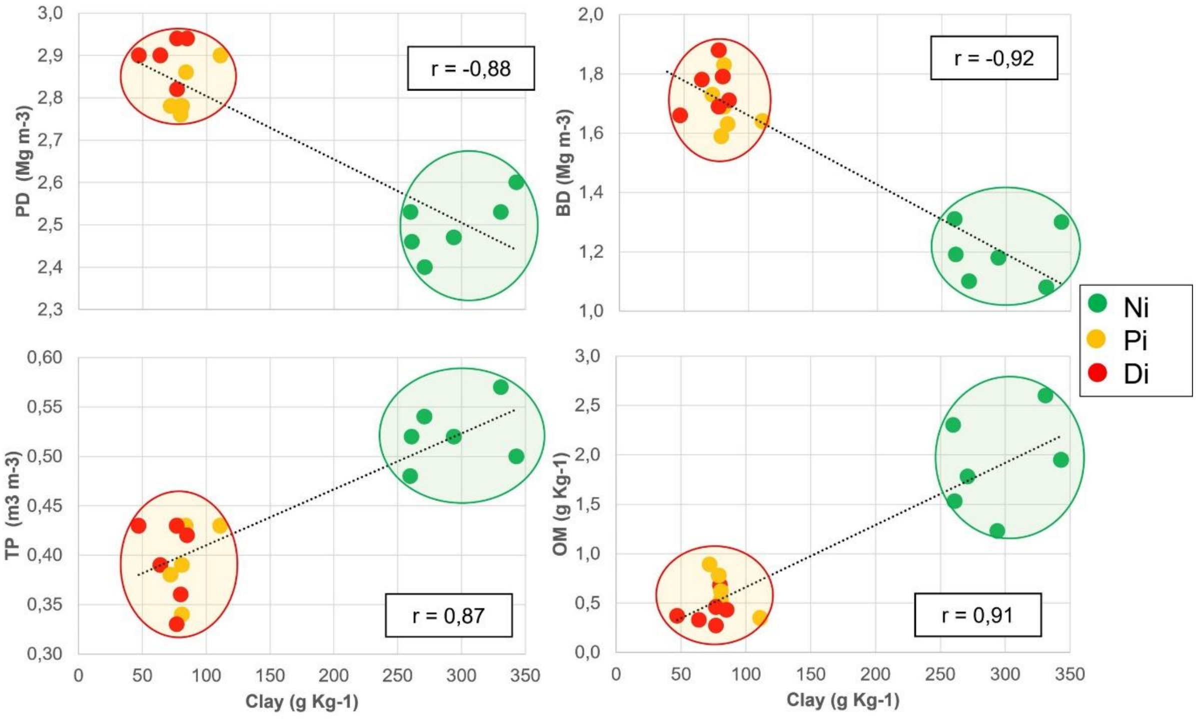


Figure 7. Relationship between clay content and a) particle density (PD), b) soil bulk density (BD), c) total porosity (TP), and d) organic matter (OM) in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted).

3.2. Load-bearing capacity of the soils

In comparison of the LBCM of the surface layers (0-3 cm) of the soils, no differences were observed between the Di and Pi soils under the different types of vegetation evaluated (Table 1), and they were clustered in a single model. In Ni in the different types of vegetation, the soils also did not differ and, therefore, they were clustered in a single model. Consequently, 2 models were obtained for the surface layer of the 9 conditions studied (Figure 8A).

Table 1. Comparison of the load-bearing capacity models [sp = 10(a + bq)] for the 0-3 cm layer in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil, according to the procedure described in Snedecor and Cochran (1989).

Model	Homogeneity	F		Decision	Model
		Linear coef. (log a)	Angular coef. (b)		
EucDi*NFDi	H	NS	NS	Cluster	
EucDi+NFDi*RFDi	H	NS	NS	Cluster	
EucPi*NFPi	H	NS	NS	Cluster	

EucPi+NFPi*RFPi	H	NS	NS	Cluster	
EucNi*NFNi	H	NS	NS	Cluster	
EucNi+NFNi*RFNi	H	NS	NS	Cluster	A1
EucDi+NFDi+RFDi* EucPi+NFPi+RFPi	H	NS	NS	Cluster	A2
EucDi+NFDi+RFDi+ EucPi+NFPi+RFPi *EucNi+NFNi+RFNi	H	NS	*, **	Don't cluster	

Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). F test of homogeneity of variance for the regression parameters fitted; H = homogeneous; *= significant at 5%, ** = significant at 1%; NS = not significant

In the 10-13 cm layer, as in the surface layer, there were no significant differences between the angular coefficients and the linear coefficients of the Di and Pi soils under the different types of vegetation, and these LBCM were clustered in a single model, as shown in Table 2. The same occurred with the LBCM of the Ni soils, which did not differ significantly and were clustered in a single model. Thus, two LBCM were obtained for the subsurface layer, as shown in Figure 8B.

Table 2. Comparison of the load-bearing capacity models [$sp = 10(a+b\Theta)$] for the 10-13 cm layer in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil, and according to the procedure described in Snedecor and Cochran (1989).

Model	Homogeneity	F		Decision	Model
		Linear coef. (log a)	Angular coef. (b)		
EucDi*NFDi	H	NS	NS	Cluster	
EucDi+NFDi*RFDi	H	NS	NS	Cluster	
EucPi*NFPi	H	*	NS	Don't Cluster	
EucPi*RFPi	H	NS	NS	Cluster	
EucNi*NFNi	H	NS	NS	Cluster	
EucNi+NFNi*RFNi	H	NS	NS	Cluster	B1
EucDi+NFDi+RFDi* EucPi+ RFPi	H	NS	NS	Cluster	
EucDi+NFDi+RFDi+ EucPi+ RFPi*NFPi	H	NS	NS	Cluster	B2
EucDi+NFDi+RFDi+ EucPi+RFPi+NFPi	H	*	NS	Don't Cluster	

* EucNi+NFNi+RFNi

Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). F test of homogeneity of variance for the regression parameters fitted; H = homogeneous; *= significant at 5%, ** = significant at 1%; NS = not significant

In the LBCM of the surface layer obtained after clustering (Figure 8A), the value of the estimated “a” parameter was 82,0 in the A1 model that clusters the original soils and 137,9 in the A2 model that clusters the Technosols. In the same way, the value of the “b” parameter was from 0,91 to 0,12, respectively (Figure 8A).

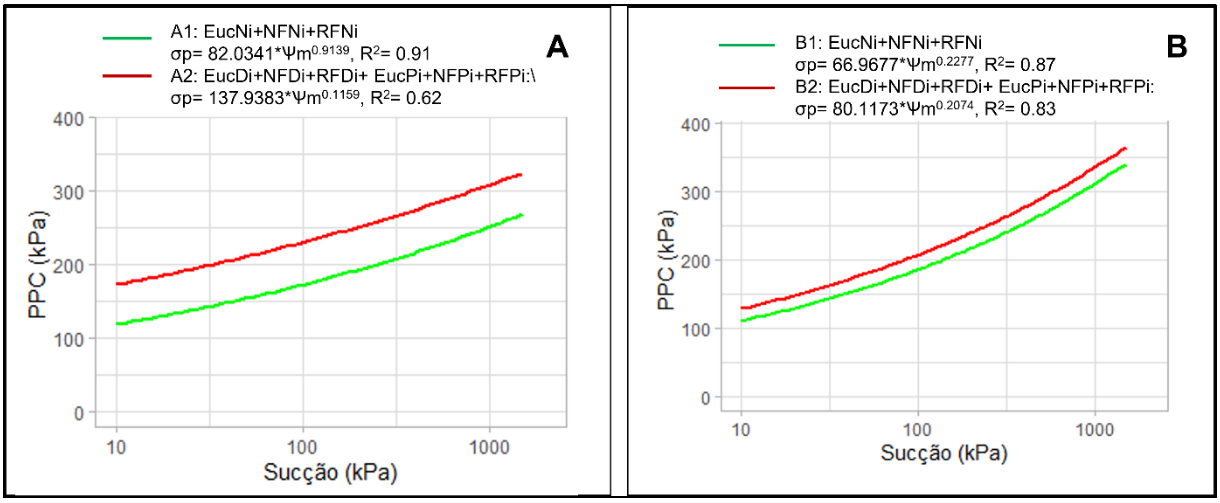


Figure 8. A) load-bearing capacity models of the surface layer (0-3 cm) and B) subsurface layer (10-13 cm) in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil. Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted).

The “A1” and “A2” models have an R^2 of 0.91 and 0.62, indicating their good fit considering that the fitting parameters had highly significant results, with values lower than 0.01 (Appendix). The A2 model has preconsolidation pressures (PCP) of around 325 kPa under a matric potential of -1,500 kPa, whereas the A1 model has values of 220 kPa at the same potential. In contrast, the coefficients of determination (R^2) of the B1 and B2 models were 0.87 and 0.83, respectively, and significant at 1%, showing the good fit of the models (Figure 8B). For these models, the a and b parameters had values of 67.0 and 80.1 (a parameter), and 0.23 and 0.21(b parameter). For the B1 model, the pre-consolidation pressure was below 350 kPa at the matric potential of -1,500 kPa, and for the B2 model, it was above 350 kPa at the same potential.

Table 3 presents the comparison of the LBCM for the 0-3 cm and 10-13 cm layers. Four final models are obtained, since there were significant differences upon making a comparison with the linear model test of Snedecor and Cochran (1989), regardless of the layer or the level of impact compared.

Table 3. Comparison of the load-bearing capacity models [sp = a*Ψm b] for the 0-3 cm and 10-13 cm layers in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil, and according to the procedure described in Snedecor and Cochran (1989).

Model	Homogeneity	Linear coef. (log a)	Angular coef. (b)	Decision
A1 0-3cm: EucNi+NFNi+RFNi * B1 10-13: EucNi+NFNi+RFNi	H	NS	*, **	Don't Cluster
A20-3cm: EucDi+NFDi+RFDi+ EucPi+NFPi+RFPi * B2 10-13cm: EucDi+NFDi+RFDi+EucPi+ RFPi+NFPi	H	NS	*,**	Don't Cluster
A1 0-3cm: EucNi+NFNi+RFNi * B2 10-13cm: EucDi+NFDi+RFDi+ EucPi+ RFPi+NFPi	H	*,**	NS	Don't Cluster
B1 10-13: EucNi+NFNi+RFNi * A2 0-3cm: EucDi+NFDi+RFDi+ EucPi+NFPi+RFPi	H	*	NS	Don't Cluster

Type of vegetation: NF (native forest), RF (revegetated forest), Euc (eucalyptus). Level of impact: Ni (not impacted), Pi (partially impacted), Di (directly impacted). F test of homogeneity of variance for the regression parameters fitted; H = homogeneous; *= significant at 5%, ** = significant at 1%; NS = not significant.

Since these models were not clustered, they conserved the values of the “a” and “b” coefficients, as the R^2 already indicated (Figure 9).

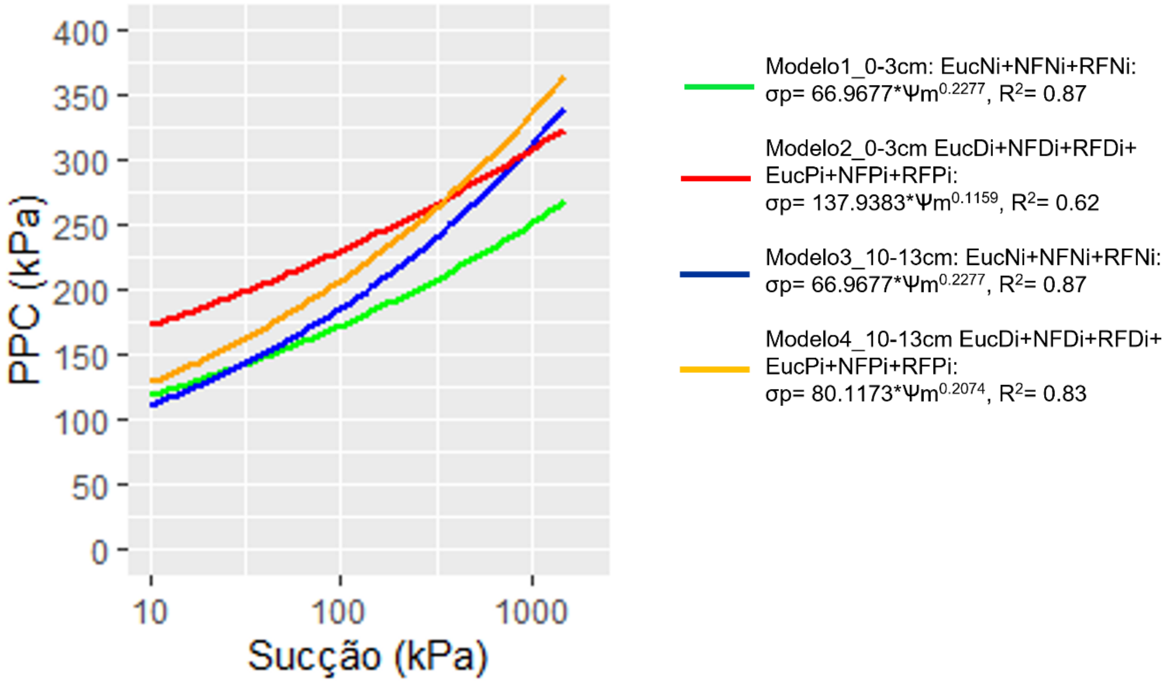


Figure 9. Final soil load-bearing capacity models in areas affected by the rupture of the Fundão Dam, Minas Gerais, Brazil.

4. DISCUSSION

4.1. Soil characteristics and physical properties

The textural variability of the soils studied was determined by the deposition of material coming from the dam with high silt and very fine sand content, and low clay content. For the total sand values, only two groups were differentiated. Thus, our research shows that as a consequence of the low coarse sand contents in the tailings that gave rise to the Technosols, the values of this particle size do not represent a criterion of differentiation among them and the Ni soils, whereas the finer sands represent a criterion of differentiation.

In this respect, Silva et al. (2015) described the particle size composition of this sediment as consisting of around 90% sand and silt and only 10% clay, compacted, and with low porosity and absence of structure. This information corroborates that of Silva et al. (2006); in similar tailings, they observed contents of around 54g kg^{-1} coarse sand, 729g kg^{-1} fine sand, 122 g kg^{-1} silt, and less than 100 g kg^{-1} clay. This information regarding the characteristics of the tailings explains the granulometry of the Technosols evaluated in this study, coinciding with the results of (Silva et al., 2021); their research showed that the silt contents in the soils impacted by the dam had a general effect on the physical properties of these soils. Similarly, in their research on Technosols formed by mining, Kozłowski et al.

(2023), characterized the texture of these soils as sandy loam because the sand fractions were greater than 50% and the clays were less than 20%. The clay content in the Technosols can also be explained by the nature of the parental material already described because, as mentioned, the newly-formed soils have characteristics received from the sediment of origin, whereas the higher contents of this size of particles in the original soils is a product of the differentiated pedogenesis that occurred in them.

The changes in granulometry can also explain the PD, which changes the physical composition and probably the mineralogical composition of the soils because of the origin of the tailings deposited. High PD in the profile of Technosolos formed from mining tailings was found in recent research (Kaczmarek et al., 2021; Shishkov et al., 2022) and was attributed to the characteristics of the origin material. In this sense, Santos et al. (2019) and Couto et al. (2021) found a predominance of iron oxides in locations impacted by the Fundão Dam. These minerals are typical of tailings dams in the iron mining processes and can explain the PD results. For example, Hematite has a PD of 5.3 5.26 Mg m-3 (Chen et al., 2019), explaining the higher particle density in the Technosols compared to the original soils with significantly greater clay content (Fig. 7a).

The results obtained in this study for BD coincide with those of (Schaefer et al., 2015; Silva et al., 2016; A. O. Silva et al., 2021; Couto et al., 2021), who evaluated depositions of tailings coming from mining, always obtaining higher BD compared to the BD in the soils without tailings. Similarly, (Radhika et al., 2020), found in their research that Technosoils produced by mining, like those in this research, presented BD above 1.7 Mg dm^{-3}, with little variability in the profile. These increases may also be related to the lower clay and high silt and sand contents, as already discussed – in Figure 7b, the soils with highest clay contents (non-impacted soils) have the lowest BD, while the Technosols, both those formed by partial impact and those formed by direct impact of the tailings, have the highest bulk densities.

However, it is noteworthy that the BD (and consequently lower TP) in these soils may have increased beyond the densification of the tailings over the period of pedogenesis that occurred in the four years after their deposition, in accordance with the principles proposed by (Ferreira, 2010). In other words, their compaction may have increased by the pedogenetic process of densification brought about in this case by the quantity of silt (content > 400 g kg^{-1}) and very fine sand (content > 200 g kg^{-1}) particles.

In the same way, the OM content in the soils is correlated with the clay values (Fig. 7d). That is because in the Ni soils, the values of organic matter were significantly greater than in the Technosols, in agreement with the results of Batista et al. (2020); Silva et al. (2021); Couto et al. (2021). This result is due to the variability of the organic matter carried by the rupture of the dam, which produced its accumulation at random in the Technosols. The reduction of OM in the Technosols is also closely related to the reduction in microbial activity in these soils (A. O. Silva et al., 2021). In this respect, Batista et al. (2020) showed that the physical-chemical properties and the presence of low bioavailable concentrations of heavy metals in the dam tailings led to changes in the microbial communities through reductions in C storage and in biogeochemical cycling of nutrients in comparison with those in undisturbed reference soils in the surroundings. This, therefore, has negative implications for ecosystem operations.

The total clay content has been indicated as the main characteristic that determines soil properties, due to its effect on soil structure, density, porosity, organic matter, and other properties (Dexter, 2004; Mazurana et al., 2017; Martín et al., 2018). In this study, this response can be seen in Figure 7 by the high correlation between clay and the other properties evaluated. There is thus a high negative correlation with PD (r = -0.88) and BD (r = -0.92), and high positive correlation with TP (r = 0.87) and OM (r = 0.91). In the same way, this figure shows the similarity of the Technosols regarding the properties evaluated, regardless of their position in the landscape, as a consequence of their formation from the tailings that were deposited at random over the original soils, which exhibited greater variability resulting from the differentiated pedogenesis in the natural environment.

On the other hand, it has already been demonstrated that high silt contents in theses soils, can result in surface crusting and consequent erosion problems (Rabot et al., 2018; Cruz et al., 2020; R. F. da Silva et al., 2021). In addition, together with the very fine sand, silt is associated with the predominance of smaller size pores, with consequent problems of permeability, imposing restrictions on water movement (Oliveira Silva et al., 2018; A. O. Silva et al., 2021). This occurs because the predominance of these particles generates a structure of greater density in which the grains of fine sand and silt occupy the spaces (plug) the pores formed by the coarser sand, leading to the predominance of small pores in the soil, as reported by (Ribeiro et al., 2007). Therefore, regarding their physical properties, the Technosols represent a challenge for management, whether for the purpose of reforestation for recovery of biodiversity or for agricultural use, considering that the tailings also reached areas under cultivation.

In contrast, the properties and characteristics of the original soils classified as sandy clay loam generally fit within what is expected for soils of this textural classification in comparison with diverse studies regarding this type of soil (Ottoni et al., 2014; Obour et al., 2019; Arruda et al., 2021). Nevertheless, this comparison does not allow differences to be seen regarding their degradation or loss of quality, which is expected in highly human-impacted soils.

4.2. Soil load-bearing capacity

For all the soils evaluated, the σ_p increased as suction decreased (Figure 9). Similar results were observed by several authors (Martins et al., 2013; Severiano et al., 2013; Andrade et al., 2017; Tassinari et al., 2019) both in studies to evaluate load-bearing capacity (LBC) and in evaluation of compaction. The reduction in soil resistance in accordance with greater moisture content is due to the fact that as soil moisture content increases, the activity of the cohesive forces of the soil and the internal friction decreases, thus leading to reduction in soil mechanical resistance (Assis et al., 2009; Paiva de Lima et al., 2013).

Technosols had higher σ_p, and this condition is closely associated with soil granulometry, as reported by (Severiano et al., 2013), whose research showed that soil resistance decreases as clay content increases. In addition, Technosols have high silt contents, and, under these conditions, the internal contact friction becomes significant, increasing soil resistance (Carrera et al., 2011).

These results coincide with those obtained by Islam (2023), who evaluated three different types of mining tailings, demonstrating that tailings with higher clay content presented lower consolidation values. In this sense, Radhika et al. (2020) affirm that tailings deposits suffer significant deformations and alterations in the proportion of voids, which, together with the effect of the weight of the material itself, produces the consolidation of these residues.

The greater resistance of the subsurface layers shown in Fig. 8 is consistent with different studies that show that the subsurface layers of the soil tend to have greater resistance than the surface layers (Oliveira et al., 2003; Araujo-Junior et al., 2011; Iori et al., 2012), which is closely related to the greater biological activity and, consequently, to the significantly greater OM of the surface layers. Technosols, however, had lower OM, as well as high variability in the different uses and layers evaluated, as a consequence of reduction in microbial activity. This generated the selection of microbial groups more adapted to the conditions of the tailings with low OM content and greater silt content, as found by (A. O. Silva et al., 2021). That makes these newly-formed soils have greater LBC, even greater in the surface layer, compared to the non-impacted soils under pressures lower than 500 kPa.

In addition to the emergency measures adopted after the collapse of the Fundão Dam, programs were later developed and monitored related to coverage and production of plant biomass, monitoring of soils (including evaluation of physical, chemical, and microbiological properties), and activities of forest restoration. At the beginning of 2019, increases were already seen in the organic matter contents through evolution of this planting (Fundação Renova, 2019; RAMBOLL, 2019).

Among the activities developed for management of the tailings, the use of a mixture of herbaceous seeds (legumes and grasses) stands out, with the aim of creating a root network able to reduce instability and sliding of the accumulated tailings (Fundação Renova, 2019). Therefore, it is quite probable that these actions, together with the pedogenesis that occurred, favored differentiation of the layers of the Technosols, generating significant differences in the LBCM.

Furthermore, the A2 and B2 models generally have greater preconsolidation pressures compared to the A1 and B1 models (Figure 9). In these models, greater load-bearing capacity is observed nearly throughout the entire suction range evaluated. However, for 1000 kPa, the B1 model, corresponding to the subsurface layer of the original soils, has an important increase, exceeding that of the A2 model. Nevertheless, the high pre-consolidation pressure at low moisture levels shown by the A2 and B2 models indicate that these soils may offer greater resistance to root development of the plants, as reported by (Dias Junior et al., 2019).

Pre-consolidation pressure depends on intrinsic and extrinsic soil factors – texture and mineralogy, soil structure and bulk density, management and use, organic matter content and characteristics, among others (Richart et al., 2005; Severiano et al., 2013; Dias Junior et al., 2019). Thus, it is possible to understand how the deposition of tailings from mining and the Technosols formed from the pedogenesis that occurred on this material have greater resistance, even comparable to the soils affected by agricultural activity (Severiano et al., 2013; Andrade et al., 2017; Martins et al., 2018; Tassinari et al., 2019), even though the Technosols are quite different from the weathered soils of Brazil regarding particle-size composition.

Considering the physical limitations described for the Technosols studied and based on the functionality of these soils, Leguédois et al. (2015) highlights the importance of a holistic approach in focus on the multifunctionality of Technosols for the provision of local ecosystem services. Said proposals, commonly aim at recovering agricultural areas degraded by agriculture, based on development of sustainable systems that can promote high resilience, and conserve natural resources (Mosier et al., 2021; Shahmohamadloo et al., 2021; Spratt et al., 2021). However, can be applied to manage not only of the areas under study here, but also the agricultural areas that were impacted by the dam rupture. We understand that from the homogeneity of the tailings, which, in turn, generated quite homogeneous Technosols, it is possible to predict the current physical condition of all the impacted soils.

To this end, several authors propose the combination of strategies commonly used in environmental restoration and soil recovery plans, that including the combination of various practices, such as cover plants, conservationist growing systems, use of organic compost, phytoremediation, reforestation and short-term rotational (LaCanne and Lundgren, 2018; Schreefel et al., 2020; Fenster et al., 2021; Kaczmarek et al., 2021; Kozłowski et al., 2023; Oliveira Filho and Pereira, 2023).

Therefore, it is recommended to continue investigating the formed Technosols to determine which management practices are the most appropriate to improve their properties.

5. CONCLUSIONS

- The higher values found for silt and very fine sand in the Technosols generated an increase in soil bulk density and a decrease in total porosity.

- The Technosols generally have the highest preconsolidation pressure values and the lowest organic matter values, resulting in greater load-bearing capacity for these soils.

- The high resistance of the Technosols is their main physical limitation, and it is necessary to combine various management practices directed toward the improvement of their physical properties and full multifunctionality.

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ARTIGO 2. SOIL COMPACTION UNDER SILAGE CORN: A COMPARISON BETWEEN MONOCULTURE AND SUCCESSION.

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ABSTRACT

Agriculture in Brazil is globally recognized for its advanced technology and high productivity in sustainable production systems. However, in silage corn cropping, traditional monoculture management with intensive use of agricultural machinery persists, along with continued traffic in cultivation areas due to the nature of its harvest. Therefore, this study aims to assess soil compaction under silage corn over two harvests and under two conditions: monoculture and succession with soybeans. The experimental design was completely randomized, and the data was analyzed using a mixed linear model to determine fixed (use and layer) and random effects (time) in the analyses. Four samplings were conducted using an Uhland sampler, collecting undisturbed samples with cylinders 2.5 cm high and 6.4 cm in diameter in two soil layers: 0-20 cm and 20-40 cm. The first samples were collected to develop Load-Bearing Capacity Models (LBCM). These were drained under different potentials and then subjected to uniaxial compression testing to conduct soil compression tests and subsequently model compaction. Three successive samplings were conducted, before and after silage corn harvesting in each cycle. Soil density (Ds), pre-compression stress (PPC), total porosity (Pt), microporosity (Mic), macroporosity (Mac), and organic matter (OM) were also determined throughout the trial. The results show that soil preparation exerted the greatest influence on soil decompaction. However, succession management proved to be more efficient in increasing soil resistance to compaction, as it showed a lower percentage of compacted samples by the end of the research in both layers that were evaluated, as well as improvements in Ds, and Mic. In soils under monoculture, there were no favorable changes in these properties, with Mic increasing and Mac decreasing. These findings emphasize the significance of interrupting the pressure cycle induced by excessive machinery traffic in soils under silage corn monoculture. This can be achieved by implementing sustainable management practices that enhance the soil's resistance to compaction.

Keywords: Compaction. Monoculture. Load-bearing capacity. Silage corn. Pre consolidation pressure.

1. INTRODUCTION

The production of cow's milk in Brazil has surpassed, for the first time in history, the mark of 30 billion liters, showing an increase of 62% compared to the results of 2006 (IBGE, 2017). By the year 2022, the Brazilian cattle herd reached a new world record of 234.4 million animals, marking a 4.3% increase from the previous year (IBGE, 2022). However, according to the Milk Map (MAPA, 2022), Brazil ranks as the third-largest milk producer globally, highlighting the limited efficiency of these production systems.

In this regard, it is important to note that milk production in Brazil originates mainly from small properties with low investment in technologies (DE OLIVEIRA et al., 2017), where agricultural and livestock activities are carried out separately (NASCIMENTO JÚNIOR et al., 2023). The areas dedicated to livestock show low yields when compared to areas under grain production systems, which employ the world's highest production technology (PINHEIRO et al., 2021), using sustainable management practices such as no-till farming, cover crops, and crop rotation (FERNANDES; TEJO; ARRUDA, 2019; KOPPE et al., 2021; NASCIMENTO et al., 2022; PEIXOTO et al., 2019a), aimed at reducing or preventing soil degradation (HUSSAIN et al., 2021). These practices have made Brazilian agriculture recognized for its high productivity in sustainable systems.

Several authors affirm that corn forage is the most used forage in these systems due to its nutritional quality and provided forage volumes (BERNARDES; DO RÊGO, 2014; DE OLIVEIRA et al., 2017; SANTOS et al., 2019; SILVA et al., 2021). However, the predominant cultivation of corn in the form of monoculture may negatively affect soil fertility and its physical properties (UENO et al., 2011; WENDLING; FILHO, 2018). According to CASTOLDI et al. (2011); LANES et al. (2006); MACHADO; FAVARETTO (2006); RESENDE et al. (2017), management of silage corn still involves intensive use of machinery from soil preparation to harvest, employing significant pressure on soils and exacerbating degradation processes, affecting its physical properties. The negative effects on soil properties due to conventional soil preparation practices used in these cultivation systems have been well-documented. Various studies have shown the detrimental impact on soil density, aggregation, organic matter accumulation, as well as water and air circulation, microbial activity, and production quality (OLIVEIRA et al., 2020; TORABIAN; FARHANGI-ABRIZ; DENTON, 2019; VIZIOLI et al., 2021)

On other hand, in more traditional systems like silage corn culture, almost all aboveground plant parts are harvested, requiring heavy machinery traffic, and applying high pressures, what usually happens in the rainy season when on damp soil (TASSINARI, 2019). Additionally, the use of forage harvesters that cut the plant row-by-row results in practically the entire area being trafficked (CRUZ; FILHO; NETO, 2011). Therefore, intensive traffic and the use of large machinery can cause significant soil alterations leading to adverse consequences such as increased root penetration resistance, changes in water and nutrient availability and flow, as well as soil aeration reduction, all indicating signs of compaction (CAMBI et al., 2017; EPRON et al., 2016).

Soil compaction is considered a form of degradation that can have serious economic and environmental consequences in global agriculture due to its effects on soil structure, plant growth, and environmental events (GÜRSOY, 2021). Several studies have shown the success of sustainable practices that include crop rotation, tropical forage intercropping, crop-livestock integration systems, cover crops, and occasional tillage in their management (BERDENI et al., 2021; GONÇALVES E SILVA et al., 2024; NASCIMENTO JÚNIOR et al., 2023; PEIXOTO et al., 2020; WHITE et al., 2023). However, for an adequate compaction management, its adequate diagnosis and assessment are necessary.

Compaction diagnosis can be carried out through the compressive behavior of the soil, which refers to the relationship between pressure applied to the soil and resulting deformations. This can be determined using different methods, notably the compression curve, which graphically expresses the relationship between applied pressure and some soil mass-volume relationship property (DIAS JUNIOR; TASSINARI; MARTINS, 2019; TASSINARI, 2019).

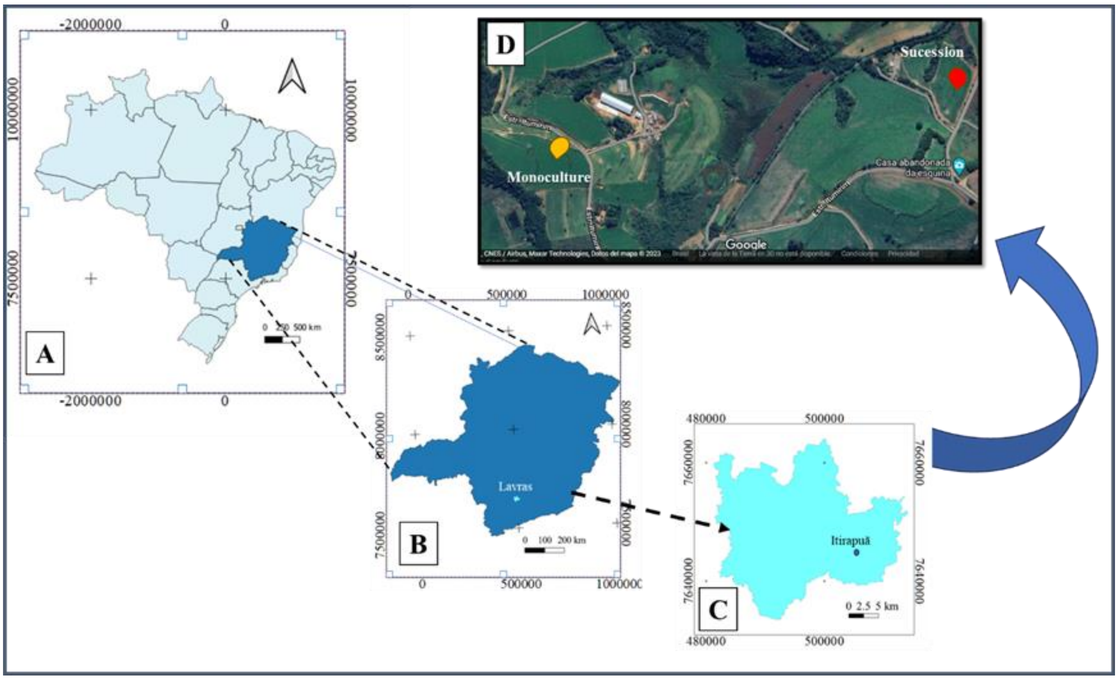
Based on the above, the aim was to evaluate soils under silage corn management in monoculture and in succession with soybeans over two crop years, to understand how these managements impact soil physical properties and its influence on soil compaction. Our hypothesis is that silage corn management in succession decreases adverse effects of excessive machinery traffic on soils under this culture, reducing the percentage of compacted samples and offering an alternative for silage corn producers to integrate more sustainable practices into their production systems.

2. MATERIALS AND METHODS

2.1. Study Area Location

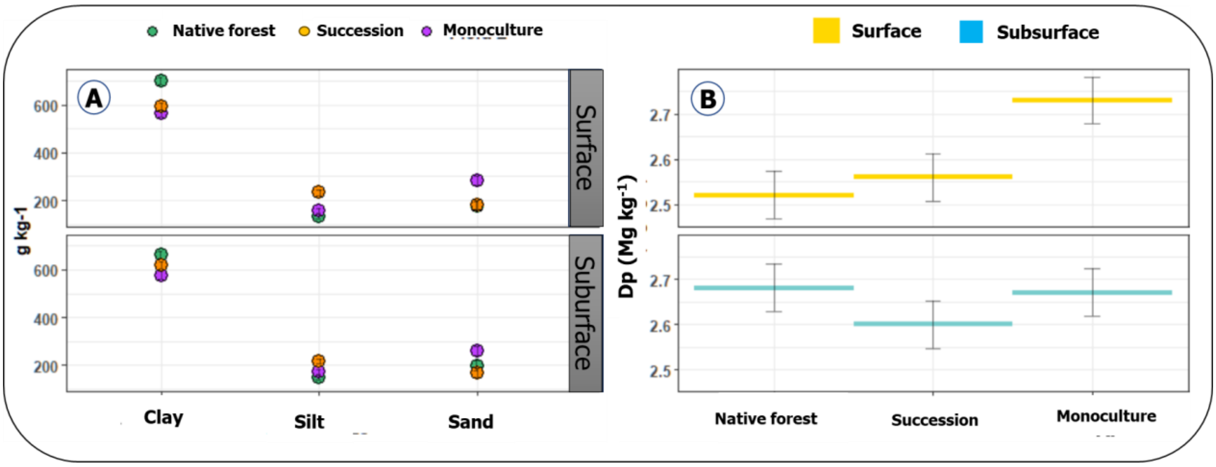
The study was conducted in the soils of a farm annually cultivated with corn for silage production located in Itirapuã, rural zone of Lavras municipality, Southern Minas Gerais, Brazil (Figure 1). The region's climate features hot and humid summers and cold and dry winters, with an average temperature of 21,6°C, and a maximum average of 27,5°C, while the minimum average is 15,7°C. The average precipitation is 1339,5 mm concentrated in November, December, and January (INMET, 2020), classified as Cwa according to Köppen's classification (ALVARES et al., 2013).

Figure 1. Location of the areas of interest. A) State of Minas Gerais (MG) in Brazil; B) Location of Lavras, MG Municipality; C) Study area within the municipality, D) Location of sampling areas (Monoculture and Succession).



The fields under study are part of a dairy farm with conventional tillage practices, which involve annual disc harrowing before sowing and occasional subsoiling. The soil usage during the crop year happens as follows: corn silage in the main crop season - corn silage in the off-season - fallow period. The harvest of the main crop and the planting of the off-season crop occur during the rainy season. The study areas are predominantly composed of Oxisols, with a clayey texture and clay content above 500 g kg-^{1}, as illustrated in Figure 2A. Two plots were chosen for the study: one where silage corn is grown during the main and off-season under conventional management, and another where a crop succession system of silage corn-soybean is implemented. Figure 2B shows the particle density values for these soils.

Figure 2. Particle size distribution (A) and particle density (B) of the studied soils.



Corn plants are harvested using a forage harvester attached to a tractor, which cuts the forage row by row, resulting in practically the entire area being trafficked.

2.2. Sampling.

All samples were collected using an Uhland-type sampler, with rings of 6.4 cm in diameter and 2.5 cm in height. The samples were wrapped in plastic film and waxed to preserve the structure and field moisture.

Soil evaluations were conducted over two crop cycles (2019-2020 and 2020-2021). In the first cycle, soils under native vegetation were sampled, as well as soils cultivated before harvest. This initial sampling was carried out to capture the physical condition of the soil at the beginning of the research and characterize the soil resistance before the traffic of harvesting machinery. Fifteen random sampling points were selected, where samples were collected in two layers: 0-5 cm and 20-25 cm, with the latter located below the plowed layer of the soil. These samples were used to develop the Load-Bearing Capacity Models for each soil (MCSC).

Subsequently, samples were collected after the corn harvest in the same cycle. In the following cycle, they were collected at pre-harvest and post-harvest of silage corn or soybeans, according to the management of each plot. Pre-harvest samplings were performed in the three days prior to harvest, and post-harvest samplings were performed in the three days following.

These successive samplings were carried out to assess the compaction and/or recovery of the physical condition of the soils due to the adopted managements. In these samplings, an average of 16 samples/layer/plot were collected, totaling 32 samples per sampling, 64 samples per cycle, and 128 samples per plot throughout the experiment for compaction assessment.

2.3. Precompression stress, load-bearing capacity models, soil physical attributes, and organic matter.

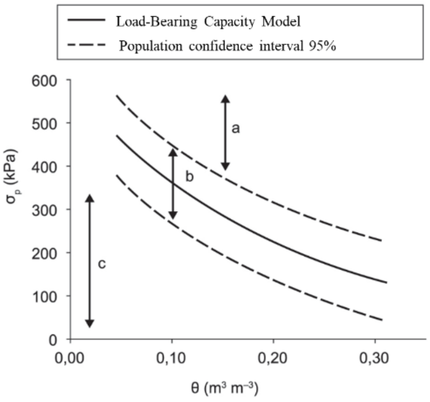
The undisturbed samples were initially prepared by removing the excess soil from the cylinders. This excess soil was air-dried and sieved (2.0 mm) for organic matter analysis (RAIJ et al., 2001). The soil texture was also analyzed by the pipette method, and particle density was determined by the pycnometer method, following the Manual of Soil Analysis Methods (TEIXEIRA et al., 2017).

Samples corresponding to native vegetation and pre-harvest (first silage corn sampling) were capillary-saturated and taken to the tension table and Richards extractor, where they were drained under matric potentials (ψ) -6 kPa, -10, -30; -100; -500, and -1500 kPa. Its mass was measured after equilibrium at each potential (KLUTE, 1986).

Subsequently, the uniaxial compression test was performed on the samples (DIAS JUNIOR; MARTINS, 2017), applying pressure with compressed air. The pressures applied to the samples were 25, 50, 100, 200, 400, 800, 1600 kPa, applied until 90% of sample deformation was achieved (HOLTZ; KOVACS; SHEAHAN, 2010), according to the proposed method. With this data, soil compression curves were developed, and precompression stress (σp) were determined (DIAS JUNIOR; MARTINS, 2017).

The LBCM for initial comparison of de soils was performed by representing the applied suction on the x-axis and the preconsolidation pressures (σp) on the y-axis (DIAS JUNIOR et al., 2005) These points were fitted to a regression of the type $\sigma p = a\Psi m^b$, where σp represents the preconsolidation pressure, Ψm is the matrix potential, and the parameters a and b represent the empirical parameters obtained from fitting the model (SEVERIANO et al., 2013), using R software (R CORE TEAM, 2020). For the subsequent assessment of soil compaction, the LBCM were developed by plotting the volumetric moisture content found at each evaluated potencial (θ) (DIAS JUNIOR et al., 2005) on the x-axis versus precompression stress (σp) on the y-axis. Using R software (R CORE TEAM, 2020), these points were adjusted to a regression of the type $\sigma p = 10^{(a + b\theta)}$, where σp is the preconsolidation pressure, θ represents the moisture content, a and b represent the parameters obtained from the adjustment. Additionally, confidence intervals were added to these models to determine the percentage of compacted samples, according to DIAS JUNIOR et al. (2005). Figure 3 presents the criteria suggested by the author for analyzing the effect of management on soil structure, where region "a" indicates additional compaction, region "b" indicates a tendency to compact if the pressure values defined by the upper limit of the confidence interval are not respected, while region "c" indicates no additional compaction.

Figure 3. Criteria for analyzing the effect of management on soil structure using the load-bearing capacity model (LBCM) with confidence intervals. Source: (DIAS JUNIOR et al., 2005)



Therefore, to analyze the effect of management on soil structure using the LBCM, undisturbed samples collected after the harvest of silage corn in the first cycle and pre and post-harvest of silage corn, as well as in the soybean succession system in the second cycle were subjected to the uniaxial compression test and used to monitor soil compaction due to mechanized operations of the crops, according to the percentage of compacted samples (DIAS JUNIOR et al., 2005; DIAS JUNIOR; MARTINS, 2017).

After the tests, the samples were dried in an oven at 105 °C for 24 hours to determine bulk density (Bd). The total pore volume (Tp) was determined by the expression: Tp = (1 – Bd/Pd), where Bd is the bulk density and Pd is the particle density. Soil macroporosity (Mac) was obtained by the difference between Tp and microporosity (Mic), with the latter considered as the water content retained at the matric tension of -6 kPa. These analyses were performed according to the EMBRAPA Soil Analysis Methods Manual (TEIXEIRA et al., 2017).

2.4. Statistical analysis

A completely randomized experimental design was set up to statistically analyze the results to Bd, PCP, Tp, Mic and OM. The data was analyzed using a mixed linear model to determine fixed and random effects in the analyses, in addition to experimental error. The variables use and layer were considered fixed effects, while time was included in the model as a random effect. The estimation method was the Restricted Maximum Verisimilitude (REML) (PINHEIRO; BATES, 2000). On the other hand, when interaction was significant, interaction plots were created. When interactions were not significant, mean comparisons were made using the Tukey test at the 1% significance level, with time as the main evaluation factor.

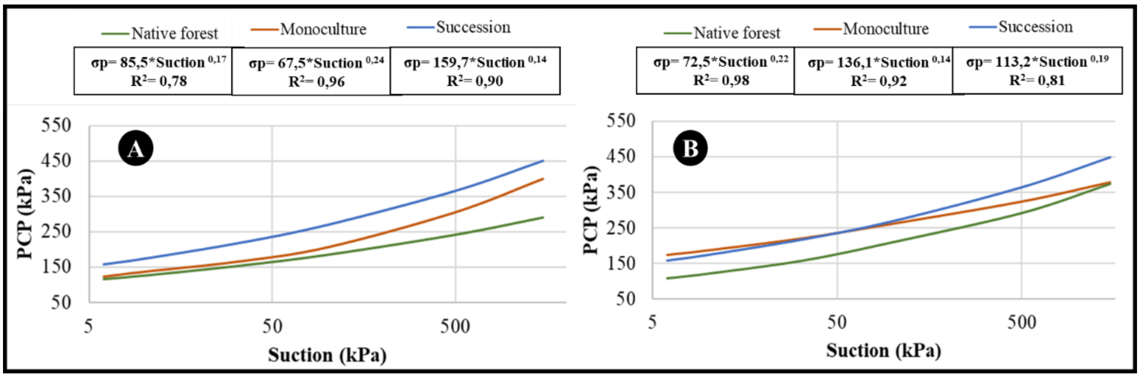
3. RESULTS

3.1. Load-bearing capacity

The Figure 4 indicates that soils under succession showed higher PCP at the beginning of the study. In the surface layer (Figure 4A), this higher PCP consistently remained throughout the range of evaluated suctions, with preconsolidation pressure values ranging between 159 kPa at the lowest suction (10 kPa) to 450 kPa at the highest applied suction (1500 kPa). On the other hand, soils under monoculture exhibited a PCP of 96 kPa at the lowest suction and 400 kPa at 1500 kPa suction. As seen in the same figure, both agricultural-use soils displayed greater resistance compared to NF soils, due to conventional management practices until the start of this research.

Conversely, in the sub-surface layer and at the lowest applied suction, soils under monoculture presented higher PCP at 175 kPa, compared to 159 kPa for soils under succession. However, at the subsequent applied suctions (>10 kPa), succession soils exhibited higher PCP (Figure 4B). In the case of NF soils, their PCP was lower than that of agricultural-use soils. Only at the permanent wilting point did NF soils show similar PCP to monoculture soils.

Figure 4. Load-Bearing Capacity Models at the beginning of the experiment for: A) Surface layer (0-5cm) and B) Subsurface layer (20-25cm) of the evaluated soils.

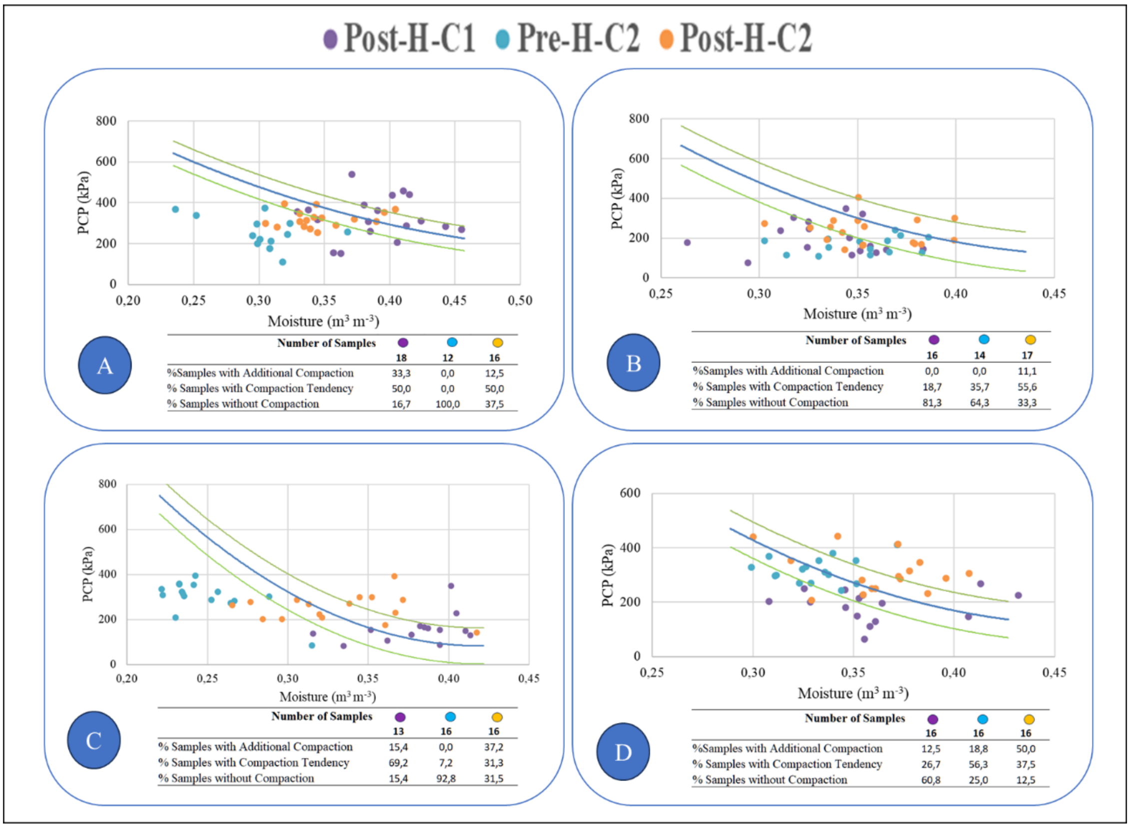


3.2. Compaction

Figure 5 shows the results of PCP in successive samplings for compaction assessment. The figure presents the results for the surface and subsurface layers of the evaluated soils. These results indicate that at the end of the first harvest 50% of samples in the surface layer showed a tendency towards compaction and 33.33% exhibited additional compaction to succession soils (Fig 5A). However, before the soybean harvest in the following crop season, the soils fully recovered without any compacted or tendency-to-compact samples. After the soybean harvest, 50% of samples showed a tendency towards compaction, with 12.5% exhibiting additional compaction.

In contrast, in the subsurface layer, there was an increase in the percentage of samples with a tendency towards compaction from the first to the second evaluation, reaching the highest value after the soybean harvest (55.6%). In this layer, samples with additional compaction were only identified in the last evaluation after the soybean harvest, with 11.1% of compacted samples.

Figure 5. Percentage of Soil Compaction under Silage corn : A) Succession superficial layer, B) Succession subsurface layer, C) Monoculture superficial layer, D) Monoculture subsurface layer.



Number of Samples	●	●	●
	18	12	16
%Samples with Additional Compaction	33,3	0,0	12,5
% Samples with Compaction Tendency	50,0	0,0	50,0
% Samples without Compaction	16,7	100,0	37,5

Number of Samples	●	●	●
	16	14	17
%Samples with Additional Compaction	0,0	0,0	11,1
% Samples with Compaction Tendency	18,7	35,7	55,6
% Samples without Compaction	81,3	64,3	33,3

Number of Samples	●	●	●
	13	16	16
% Samples with Additional Compaction	15,4	0,0	37,2
% Samples with Compaction Tendency	69,2	7,2	31,3
% Samples without Compaction	15,4	92,8	31,5

Number of Samples	●	●	●
	16	16	16
%Samples with Additional Compaction	12,5	18,8	50,0
% Samples with Compaction Tendency	26,7	56,3	37,5
% Samples without Compaction	60,8	25,0	12,5

On the other hand, in soils under monoculture of silage corn (Figure 5C and 5D), there is an increase in the number of compacted samples throughout the research. In the surface layer, the behavior was variable, with a decrease in the number of compacted samples before the second cycle's harvest and an increase after the harvest in the same cycle (Figure 5C). In the subsurface layer, compacted samples were found in all evaluations, with the lowest value in the first evaluation after the first cycle's silage corn harvest (12.5%) and the highest value at the end of the second cycle (50%) as shown in (Figure 5D).

3.3. Soil Properties

Interactions between the management and layer factors over time were significant (p-value < 0.01) for the assessed properties, except for organic matter. Thus, the differentiated effect that management has on soil layers over time is demonstrated.

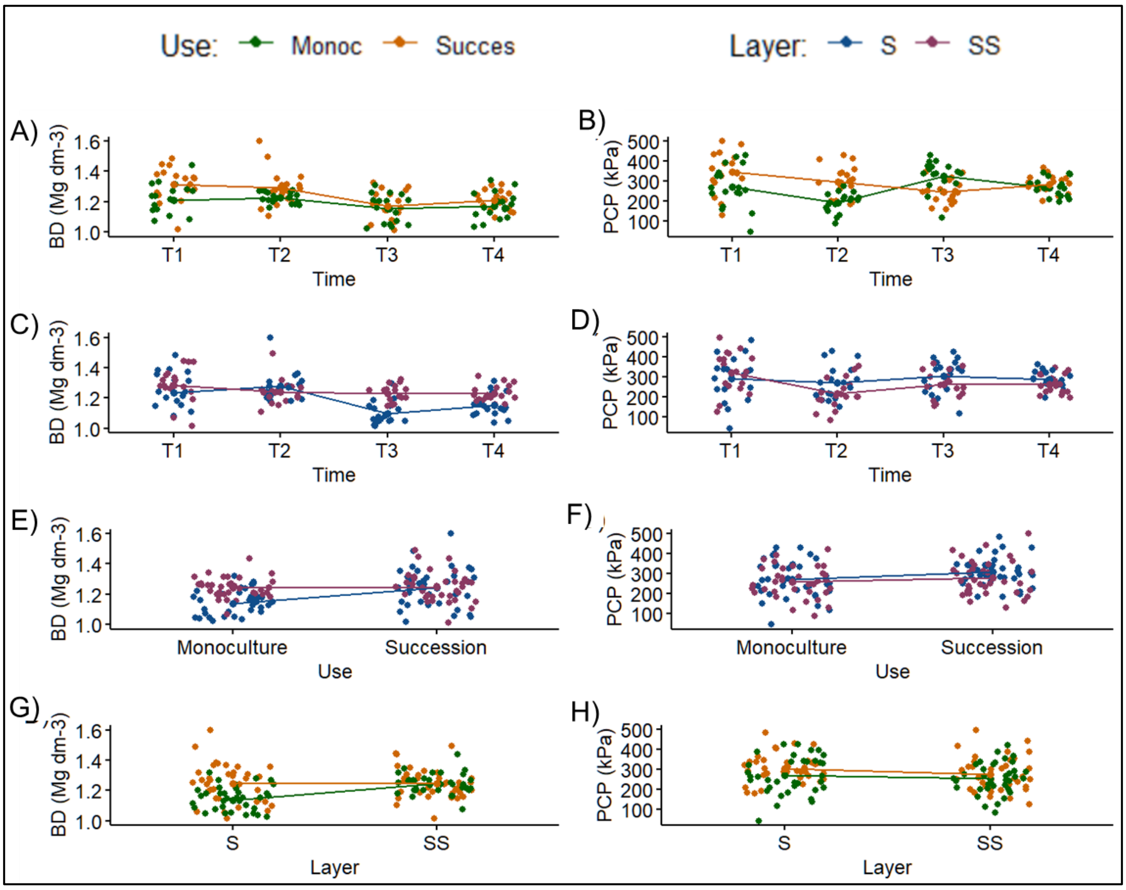
In Figure 6, the interactions of different levels of the usage and layer factors over time for properties Bd and PCP are presented. Complex interactions both when considering the usage factor within time levels (Figures 6A, 6B) and when considering the layer factor levels over time (Figures 6C, 6D) were observed.

These complex interactions led to changes in ranking for Bd and PCP. Soils under succession presented significantly higher values of Bd and PCP in the first two evaluations (T1 and T2) with an average of 1,30 Mg dm-3, compared to 1,22 Mg dm-3 for soils under monoculture. However, in the third evaluation (T3), the Bd of soils under succession dropped to 1,17 Mg dm-3, coming to be very close to soils under monoculture (1,15), and increased again in the fourth evaluation (1,21 Mg dm-3) (Figures 6A and 6B).

The same trend is observed for these properties when looking at the interactions of the two-layer levels (surface and subsurface) over time (Fig 6C and 6D). Thus, soils in the surface layer had the highest values for Bd and PCP in the first evaluation (T1), but Bd values were so variable in the surface layer that it exceeded and then decreased again. In T3 and T4, the subsurface layer of soils had higher Bd values with an average of 1,23 Mg dm-3 at the end of the evaluations, while in the surface layer, the average was 1,15 Mg dm-3. For PCP, only the initial assessment showed higher values in the subsurface layer for this property.

In the other interactions assessed, the relationship between the factors on the soil properties was straightforward. Bd and PCP responded to the combination of factors without changes in ranking over time (Figures 6E-6H).

Figure 6. Interaction graphs for bulk density (Bd) and pre-consolidation pressure (PCP). T1: Pre-harvest, Cycle 1; T2: Post-harvest, Cycle 2; T3: Pre-harvest, Cycle 2; T4: Post-harvest cycle 2



In Figure 7, the average values of Bd and PCP in different assessments conducted for each layer can be more clearly observed. It is evident that in the initial assessment, soils under succession showed significantly higher values of Bd and PCP compared to soils under monoculture. However, this difference decreased over time, until T3 when PCP values were already lower in succession, in the superficial and subsurface layer (Figures 7B).

Figure 7. The average values of bulk density (A) and pre-consolidation pressure (B) in the superficial and subsurface layers of the studied soils were evaluated over two crop cycles.

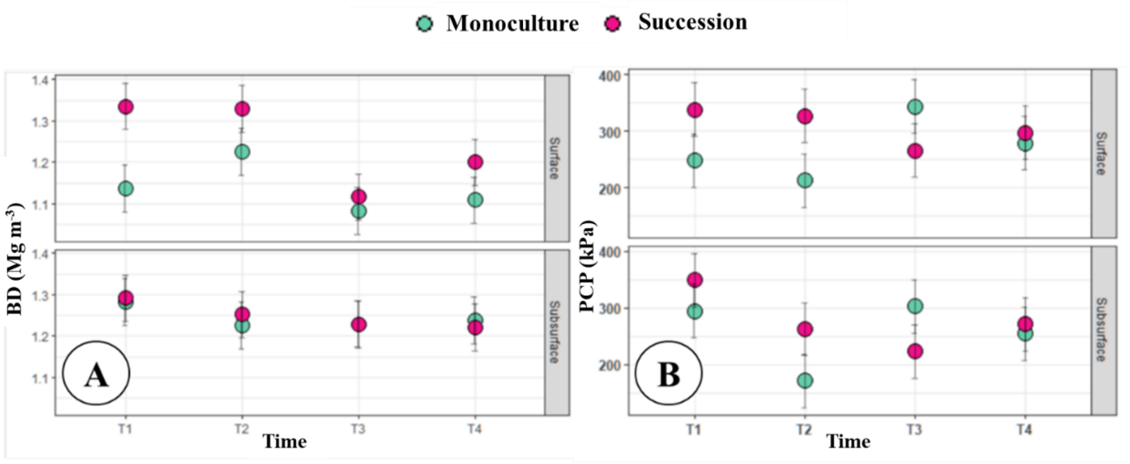
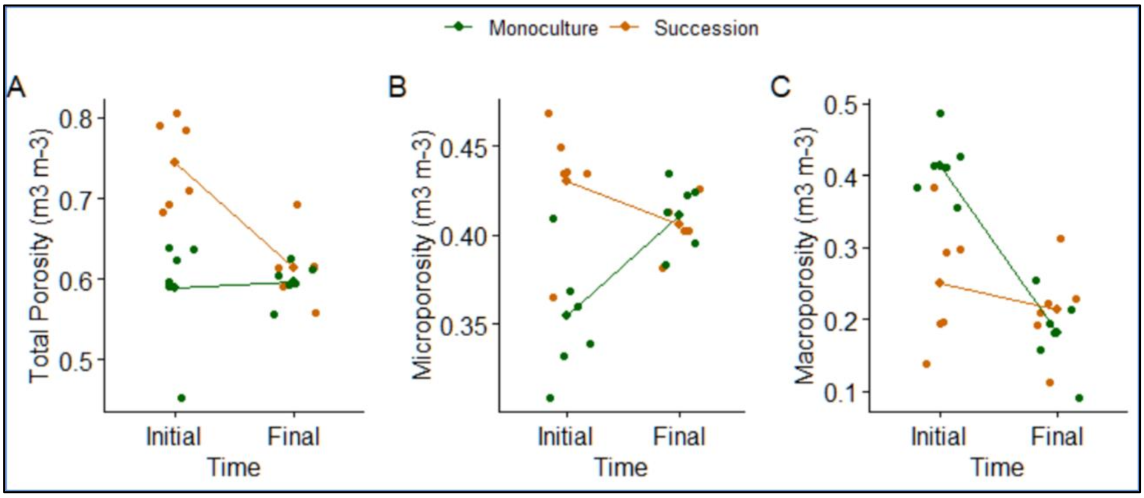


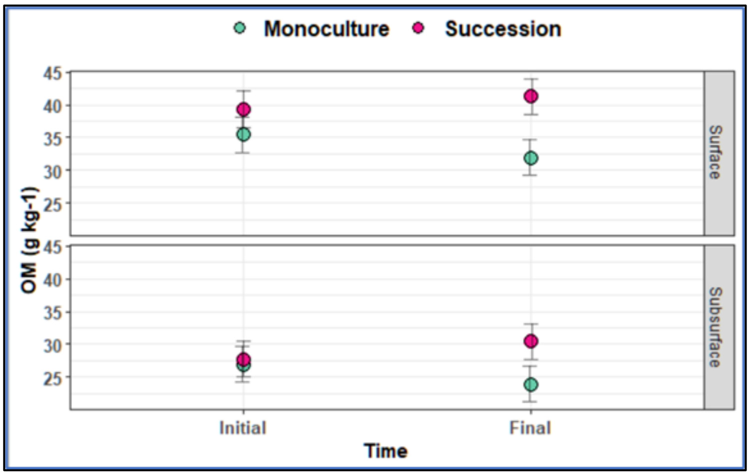
Figure 8 illustrates the variation in Pt (total porosity), Mic (microporosity), and Mac (macroporosity) values over time. Initially, total porosity and microporosity were notably higher in soils under succession (Figures 8A and 8B), with significantly lower macroporosity values compared to monoculture soils (Figure 8C). However, after two crop cycles under succession management, the Pt and Mic values decreased significantly. In contrast, soils under monoculture showed an opposite trend with a considerable increase in Mic values (Figure 8B) and a significant decline in macroporosity values, remaining below the values observed in soils under succession (Figure 8C).

Figure 8. Total Porosity, Microporosity, and Macroporosity results during the Evaluation Period.



Furthermore, OM values also exhibited highly significant differences due to the time:layer interaction, as expected in this research due to the accumulation of organic matter on the soil surface (Figure 9). When comparing the OM values in the evaluated uses, we see that there were significant differences in the final evaluation for both uses.

Figure 9. Organic matter values in the superficial and subsurface layers of the soils, evaluated at the beginning and end of the study.



4. DISCUSSION

The research findings suggest that soils with higher LBC (Figures 4a and 4b) may have less restrictive physical properties after rotating with soybean, compared to soils under continuous monoculture of corn meant for silage.

In the initial soil compaction assessment, conducted immediately after the harvest of cycle 1, higher percentages of samples with additional compaction and a tendency towards compaction were found for both soils assessed (Figure 5). These outcomes are a consequence of the conventional management of silage corn monoculture over three cycles, aligning with the findings of AKSAKAL; ÖZTAŞ (2010); GÜRSOY, (2021). However, it is evident within the same figure that before the second cycle harvest, there was complete recovery of soil compaction in the surface layer. This recovery is believed to result from the routine soil preparation to which the soils are subjected under silage corn cultivation.

However, this effect was not enduring, following the harvest of the entire corn plant in the second cycle, the soils showed an increase in the percentage of compacted samples and with toward compaction, reaching values of 37.2% in the surface layer for soils under monoculture and 12.5% for soils under succession. The results in soils under monoculture resemble the research of JÚNNYOR et al. (2019); SANDOVAL et al. (2020); SEVERIANO et al. (2013), who demonstrated in their research that continuous machinery traffic, including harvesters and tractors with transshipment, increases soil compaction in the management of crops such as sugarcane and coffee. In this regard, CHERUBIN et al. (2016); GARCIA et al. (2020)confirm that soil preparation for monoculture cultivation over extended periods alters aggregate stability, leading to compacted layers.

Additionally, because of continuous traffic in soils under monoculture, there has been a progressive increase in additional compaction in the subsoil layer. In contrast, in soils under succession, this pressure history has been interrupted, leading to an improvement in the structural quality of the soils. Similar findings were reported by (WANG et al., 2022), whose research showed that the more compacted the soils are, the more they are affected by agricultural machinery traffic.

The compacted samples at a depth of 20-40 cm in soils under monoculture made up 50% of the total samples collected. This type of compaction, known as plow pan, occurs in the layer just below the soil preparation depth when soils are repeatedly cultivated at the same depth, as was the case in soils under monoculture in this research. Similarly, WANG et al. (2022) demonstrated that tractors with heavy loads generated greater additional stress on the soil in deeper layers, occurring in soils under monoculture, where the traffic of machinery loaded with the entire plant harvest was predominant. In contrast, soils under succession exhibited 11,1% of samples with additional compaction in the same layer, demonstrating the positive effect of changing land use during a season on soil, increasing soil resistance to compaction.

The results also emphasize the impact of harvest on soils with moisture content above 0,40 m3 m-3 (Figure 5). The greater number of samples with additional compaction and a tendency toward compaction observed is concentrated around this moisture level. Studies have shown the effect of moisture as a regulating factor in soil compaction (AKSAKAL; ÖZTAŞ, 2010; AZEVEDO et al., 2022; DAIGH; DEJONG-HUGHES; ACHARYA, 2020). This is because the LBC of soils depends on their moisture content, making their susceptibility to compaction even more critical when subjected to pressures above their LBC at inadequate moisture levels (DIAS JUNIOR; PIERCE, 1995; KONDO; DIAS JUNIOR, 1999).

These results demonstrated that soils under succession exhibited higher susceptibility to compaction in the surface layer. However, the succession involving soybeans increased their resilience by the end of the study. Conversely, in soils under monoculture, the subsurface layer proved more susceptible to compaction. The continuous management under corn silage monoculture led to this condition persisting until the end of the research, with approximately 50% of the samples being compacted.

In Figures 6 and 7, improvements in the soil's physical properties due to succession management can be observed, with a significant decrease in Bulk Density (BD) and Pre-Consolidation Pressure (PCP). Conversely, in soils under monoculture, these properties tend to either remain constant or increase, negatively impacting soil structural quality. Studies have demonstrated the correlation between compaction and other physical properties of soils. For example, in the evaluation of structural quality in mechanized coffee areas, SANDOVAL et al. (2020) found impacts on BD and LBC. Similarly, SOUZA; COOPER; TORMENA (2015) discussed the effects of compaction on structure and aggregation, influencing porosity and BD. In a similar research line, AKSAKAL; ÖZTAŞ (2010) observed a reduction in water infiltration and plant development, along with increases in BD and soil strength.

It is important to highlight that the results obtained for PCP (Figures 6B and 7B) explain the soil compaction behavior more comprehensively than Bulk Density (Figures 6A and 7A). This occurs because PCP is a more complex parameter, described as an indicator of soil structure sustainability (IORI et al., 2013; SEVERIANO et al., 2010). It quantifies the soil's mechanical resistance and the maximum pressure that must be applied to prevent compaction (ARAUJO-JUNIOR et al., 2011; MARTINS et al., 2018; PAIS et al., 2013; TASSINARI et al., 2019). Moreover, PCP is affected by various soil attributes, such as moisture, organic matter, texture, soil density, type, and concentration of iron oxides, which in turn determine the cohesive and adhesive forces between soil particles (ANDRADE, 2019; IMHOFF, 2002; MAZURANA et al., 2017; SANDOVAL et al., 2020), providing more reliable results regarding soil compaction.

In terms of Total Porosity (Tp), higher values were initially obtained in soils under succession, which were more compacted at the time of assessment. However, this Tp could be dominated by structural pores or Micro Porosity (MP), representing 56% of TP in these soils. By the end of the study, these soils exhibited a reduction in Tp and Mic, indicating a recovery in their physical quality. In contrast, soils under monoculture showed an increase in Mic accompanied by a decrease in Mac, as reported by (NGOLO, 2019; OLIVEIRA et al., 2004), who found an inversion in Mac and MP values due to soil compaction. These changes impose limitations on soils, creating a barrier to water movement (AZEVEDO et al., 2022; GÜRSOY, 2021; SANDOVAL et al., 2020).

Although no significant differences were found for the same use in both initial and final assessments, significant differences were observed between the evaluated uses at the beginning and end of the research for both layers. This was due to the increase in Organic Matter (OM) in soils under succession and the decrease of this attribute in soils under monoculture. Therefore, soils under succession demonstrate a positive effect on soil OM content, which is consistent with other research where succession management favored increases in soil OM (DA SILVA et al., 2017; GMACH et al., 2018). Similarly, n his meta-analysis on the effect of crop diversity on organic matter dynamics, (MCDANIEL; TIEMANN; GRANDY (2014), found that adding one or more crops in rotation to a monoculture increased organic matter of the soil.

In this study, the accumulation in soils under succession in the final evaluation is related to OM storage after the soybean crop. This result also explains the lower values of Precompression Stress (PCP) found in these soils, which coincides with the findings of SILVEIRA et al. (2022). They found a negative interaction between these two attributes: higher OM resulting in lower PCP. This reasoning can also be used to explain the decrease in microporosity values in soils under succession, as organic matter influences the formation of more stable soil aggregates (PEIXOTO et al., 2019b), improving its porosity.

These results demonstrate the effect of seasonal crop succession on soil compaction resistance and physical properties in soils compacted by conventional silage corn management, indicating that more sustainable systems can deliver better results, positively impacting both productivity and environmental protection. The objective should be the progressive incorporation of proven sustainable and efficient management practices applicable to silage production.

In this regard, MACEDO (2009) emphasizes that Integrated Crop-Livestock Systems (ICLS) are a possibility for annual agriculture, improving straw production and soil properties, besides promoting the rational use of inputs and increasing employment and income in rural areas. As support for this proposal, we have the results of (NASCIMENTO JÚNIOR et al., 2023), who assessed soil compaction caused by animal trampling in ICLS and demonstrated that animal trampling in grazing during the dry season is not responsible for disseminating soil structural degradation in ICLS and can contribute to the physical improvement due to loosening of soil biological factors.

Similarly, when evaluating integrated systems with tropical forages for soil cover, GONÇALVES E SILVA et al. (2023) demonstrated its efficiency for biomass production and nutrient cycling, optimizing soil nutrient use and contributing to agricultural system sustainability in tropical regions. In the same research line, GONÇALVES E SILVA et al. (2024) concluded that Integrated Crop-Livestock Systems tested by them increased the amount of carbon assimilated in the ecosystem through photosynthesis, improving the potential carbon sink, soil health, and maintaining a sustainable production system.

In addition, ICL systems can contribute to the reduction of greenhouse gas (GHG) emissions, mainly nitrous oxide, by reducing the use of nitrogenous fertilizers (GONÇALVES E SILVA et al., 2023). On other hand, incorporating grain legumes or cover cropping can enhance soil water conservation, and increase system productivity, soil organic carbon, and microbial activity and diversity, due to increased carbon rich root exudates, nutrients, moisture, and ambient oxygen, also can further promote aggregate stability, and biological soil health (FARMAHA; SEKARAN; FRANZLUEBBERS, 2022; MARK-ANTHONY IHESHIULO et al., 2023; MCDANIEL; TIEMANN; GRANDY, 2014).

5. CONCLUSIONS

- The soils under the succession initially exhibited higher LBC. However, by the end of the study, they demonstrated a lower percentage of compacted samples, indicating greater resistance to compaction.

- In soils under succession, there was a reduction in Ds, PCP, and Mic, showing greater resilience, which is directly related to the increase in OM values.

- Pre-consolidation pressure proved to be an excellent indicator of soil structural quality because its results agree with the results obtained in the compaction evaluations, recording what is actually happening in the soil.

- In contrast, soils under monoculture, in addition to lower compaction resistance, they underwent a significant increase in Mic values. This emphasizes that monoculture of silage corn is highly detrimental to the soil. Therefore, it is necessary to incorporate sustainable management alternatives. These alternatives should alleviate the historical pressure imposed by machinery and safeguard the soil to positively impact its properties.

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TERCEIRA PARTE: CONSIDERAÇÕES FINAIS

CONSIDERAÇÕES FINAIS

O objetivo desta tese foi avaliar a qualidade estrutural dos solos utilizando pressões de pré-consolidação e modelos de capacidade de suporte de carga. Aqui foram utilizadas essas metodologias em duas pesquisas bem contrastantes. Tecnossolos formados de rejeitos da mineração e Latossolos sob milho para silagem. A análise da qualidade estrutural foi feita considerando outras propriedades dos solos: densidade de solo, porosidade total, distribuição do tamanho de partículas, macroporosidade e microporosidade.

Ao considerar as hipóteses iniciais do trabalho, vemos que foram atendidas, assim como os objetivos foram alcançados. Nossos resultados mostraram que os Tecnossolos apresentaram a maior capacidade de suporte de carga, produto dos altos conteúdos de silte e areia muito fina que determinaram o adensamento do solo, decréscimo na porosidade total e altos valores de pressão de pré-consolidação, que comprometem a sua qualidade estrutural. Assim, a principal restrição desses solos é a sua alta resistência, sendo essa uma condição restritiva para o crescimento das plantas.

Os Latossolos sob milho silagem avaliados nesta tese, mostraram-se mais degradados quando se faz uso contínuo da monocultura, com incremento significativo da microporosidade, que supõe limitações para o movimento da água e o ar, além de menor resistência à compactação como foi demostrado nas porcentagens de amostras compactadas. Já os solos sob sucessão, com a maior capacidade de suporte de carga ao início da pesquisa, apresentaram ao final das avaliações a menor porcentagem de amostras compactadas, evidenciando que o manejo aplicado permitiu efetivamente mitigar os efeitos do contínuo tráfego de maquinários, rotineiro na monocultura. Neste manejo, os solos apresentaram maior resistência à compactação, diminuição da densidade, pressão de pré-consolidação e microporosidade. Assim, considera-se que a implementação de práticas de manejo mais sustentáveis nesses solos, vai favorecer a sua qualidade estrutural.

Por tanto, as metodologias empregadas nesta pesquisa, mostraram-se eficientes na avaliação da qualidade estrutural, tanto em solos adensados pela pedogênese, quanto em solos compactados pelo uso de práticas agrícolas notadamente inadequadas.