UNIVERSIDADE FEDERAL DE LAVRAS

PEDRO ANTÔNIO NAMORATO BENEVENUTE

IMPROVING SOIL QUALITY AND PLANT GROWTH IN DENSE CAMBISOL: LONG-TERM EFFECTS OF DEEP TILLAGE IN COFFEE CULTIVATION

LAVRAS – MG

2023

PEDRO ANTÔNIO NAMORATO BENEVENUTE

IMPROVING SOIL QUALITY AND PLANT GROWTH IN DENSE CAMBISOL: LONG-TERM EFFECTS OF DEEP TILLAGE IN COFFEE CULTIVATION

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. Dr. Bruno Montoani Silva
Orientador

Prof. Dr. Geraldo César de Oliveira
Orientador (Aposentado)

LAVRAS – MG

2023

Ficha catalográfica elaborada pelo Sistema de Geração de Ficha Catalográfica da Biblioteca Universitária da UFLA, com dados informados pelo(a) próprio(a) autor(a).

Namorato Benevenute, Pedro Antônio.
Improving soil quality and plant growth in dense Cambisol: Long-term effects of deep tillage in coffee cultivation / Pedro Antônio Namorato Benevenute. - 2023.
208 p. : il.

Orientador(a): Bruno Montoani Silva.

Tese (doutorado) - Universidade Federal de Lavras, 2023.
Bibliografia.

1. Deep preparation of planting furrow for coffee. 2. Soil physical quality indicators. 3. Computed tomography applied in soil. I. Montoani Silva, Bruno. II. Título.

PEDRO ANTÔNIO NAMORATO BENEVENUTE

IMPROVING SOIL QUALITY AND PLANT GROWTH IN DENSE CAMBISOL: LONG-TERM EFFECTS OF DEEP TILLAGE IN COFFEE CULTIVATION

MELHORIAS DA QUALIDADE DO SOLO E O CRESCIMENTO DE PLANTAS EM CAMBISSOLO DENSO: EFEITOS A LONGO PRAZO DO PREPARO PROFUNDO NO CULTIVO DO CAFEEIRO

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.

APPROVADA em 19 de junho de 2023.

Dr. Aldir Carpes Marques Filho	UFLA/DAG
Dr. Milson Evaldo Serafim	UFLA/UFMT
Dr. Richard Heck	University of Guelph – Canada
Dra. Samara Martins Barbosa	UFLA/DCS

Prof. Dr. Bruno Montoani Silva
Orientador

Prof. Dr. Geraldo César de Oliveira
Orientador (Aposentado)

LAVRAS – MG
2023

A minha querida, amada e guerreira Mãe, Janaina Namorato de Souza, por seu amor constante e por me proporcionar uma vida simplesmente apaixonante e apaixonada.

A minha avó Neide Namorato de Souza (in memoriam), por seu exemplo de mulher, serva de Deus, guerreira, por ser a nossa base familiar, por seu amor infinito e incondicional, sobretudo por nunca ter desistido de concretizar os sonhos de todos aqueles que a cercavam.

DEDICO

AGRADECIMENTOS

A Deus pela vida e pela certeza de que Ele está sempre comigo, abençoando e protegendo-me;

A Universidade Federal de Lavras; Ao Departamento de Ciência do Solo; À CAPES; FAPEMIG; e ao CNPq, pela bolsa de doutorado concedida; Aos Professores do DCS por todo auxílio e companheirismo em especial aos meus queridos amigos Dulce, Doroteo, José Roberto, Alessandra e Denise;

Aos meus Orientadores Geraldo César de Oliveira e Bruno Montoani Silva pelo companheirismo, dedicação, por sempre me escutar e compartilhar comigo experiências que visam o meu crescimento pessoal;

À Fazenda Frade; Ao produtor e amigo de laboratório e campo Vinícius Moribe Pereira e família, pela doação da área experimental e por seu interesse na pesquisa associada à Física do Solo;

Ao meu companheiro de projeto Fernandes Antônio, por sua amizade, consideração e auxílio na realização deste trabalho, sem o seu esforço e auxílio este projeto não seria o mesmo, principalmente durante o período da pandemia, obrigado amigo por tudo;

To Professor Richard Heck, for the opportunity to have studied part of my PhD in Canada, for all experiences in the field trips, and for introducing me to outstanding professionals, Farzad, Fatemeh, Bosun, and Mary;

À minha mãe Janaina, por seu amor imensurável, zelo, carinho e por me proporcionar uma vida simplesmente maravilhosa. Mãe, você é um exemplo de mulher na minha vida, te amo;

Ao meu padrasto José Maurício Marques por todo auxílio e apoio durante esses 4 anos de doutorado, sem você minha vida teria sido muito mais complexa associada à essa jornada Lavras - Cataguases, Cataguases - Lavras e mudanças, Muito Obrigado;

À minha irmã Geovana pelo carinho e amor infinito, juntamente com os meus sobrinhos Davi e Murilo, amo vocês;

Aos meus padrinhos Maria Cecília e Ewaldo por todo seu amor, companheirismo e por momentos muito felizes compartilhados juntos;

Às minhas irmãs do coração Rafaela e Gabriela por me amarem intensamente. Ao meu cunhado do coração Raphael por me proporcionar momentos inesquecíveis regrados de muita comida boa, conforto e o mais importante, conversas excelentes; E aos meus afilhados Benício, Stella e Lis, amo vocês!

À toda minha família que me auxiliou e me amou mesmo eu estando longe de casa;

A todos os integrantes da Família Lasmar, em especial a minha amiga Karina Lasmar por ter me apresentado as melhores pessoas, as quais eu nunca sonharia em conhecer; Carolina Lasmar você faz os meus dias tristes ficarem, suportáveis, maravilhosos e extremamente felizes, eu amo todos vocês! Vocês são uma família divertida, sincera e honesta;

Aos amigos do DCS e UFLA que me proporcionaram momentos inesquecíveis, Maila, Gustavo, Letícia, Monna Lysa, Filipe, Fernanda, Everton, Renata, Vanessa, Raphael, André, Lázaro; Patrine, Marlon e Isabella. Maila e Gustavo, vocês foram essenciais durante todo o meu doutorado, obrigado pela nossa amizade, pelos muitos e longos estudos tanto da pós-graduação quanto de Inglês e claro nossos inesquecíveis momentos de compartilhar alegrias;

À minha fiel amiga e inesquecível iniciação científica Mariany, por todo auxílio e zelo para com este trabalho, jamais esquecerei o quanto esforço você colocou em todas as análises;

À Samara Martins Barbosa por ter me ensinado a ser um pesquisador maior e melhor;

À Érika Andressa da Silva, pela amizade e por sempre me dar conselhos;

A Dona Cida, mais conhecida como Dona Cidinha, por ter me acolhido em sua pensão e por ter me proporcionado momentos de diversão e conversas maduras junto a sua família;

Ao professor Antônio Antonino, juntamente com o departamento de Energia Nuclear da Universidade Federal de Pernambuco (UFPE) pelo apoio e suporte na realização das análises de tomografia computadorizada.

À família Pita, que me acolheu no Canadá durante o meu doutorado sanduíche, especialmente minha querida, amada e inesquecível Landlady Cleide Pita que me tratou igual a um filho durante 1 ano e 3 meses que passei fora do Brasil. À minha amada e amiga/irmã Patrice Pita por ter me proporcionado momentos inesquecíveis e por ser uma excelente confidente e conselheira. À Gabriela Urquhart & Family por ter me proporcionado momentos de conforto e de muita confiança e principalmente em me fazer saber que eu sou capaz;

À Grazi, Benevenuto, Isabela, Maria Luiza, Joana, Natália, Dri, Suellen, Lucas, Jéssica, tantos outros amigos brasileiros que fiz no Canadá, vocês foram maravilhosos na minha vida;

À Yara, pela parceria de sempre em todos os eventos do curso de inglês e por momentos inesquecíveis desbravando a cultura canadense, obrigado amiga;

To the many friends I left behind in Canada, the Calvary church family, Karen & Family, Arlie, Ann & Family, Adam & Family, Karen, Willian, Ben, Vishurut, Michell, Daniella, Michelle, and many others. You were and will continue to be unforgettable in my life. You can't imagine how hard it was to say goodbye.

MUITO OBRIGADO! THANK YOU VERY MUCH!

“O mais legal do trabalho em equipe é ver o seu melhor se transformar em excelência com a força dos outros integrantes”

“Bem sei que tudo podes Senhor, e nenhum dos teus planos podem ser frustrados.”

Jó-42:2

“Consagre ao Senhor tudo o que você faz, e seus planos serão bem-sucedidos.*”*

Pv-16:3

“A paciência é amarga, mas seu fruto é doce!”

Jean-Jacques Rousseau

RESUMO

A demanda por terras para o cultivo de café aumentou devido à popularidade desta bebida, inclusive em solos com restrições físicas e hídricas, como os Cambissolos. Embora a maioria dos plantios seja em áreas de sequeiro, é crucial estratégias de manejo para otimizar o uso da água no solo. O investimento em tecnologia de preparo inicial, como a abertura de sulcos profundos de plantio, é crucial para garantir o sucesso a longo prazo e melhorar a qualidade físico-hídrica do solo. Nesse contexto, foram realizados três estudos em uma área experimental de Cambissolo em Nazareno, Minas Gerais, Brasil. Os preparos de solos são distinguidos em relação à abertura do sulco de plantio: SP40 (até 0,40 m pelo sulcador); SP60 (até 0,60 m pelo Big Mix, homogeneizador de solo); SP80 (até 0,80 m pelo Dreno, subsolador) e distinguidos em relação à correção química em profundidade pela calagem adicional (SP60AL; SP80AL) ou pela mistura com gesso, serpentinito e fosfato natural (SP40M; SP60M; SP80M). O primeiro estudo analisou efeitos ao longo de cinco anos de diferentes estratégias de cultivo profundo e correção química do sulco de plantio na qualidade física do solo e no crescimento das plantas de café. Os resultados mostraram que o preparo do sulco profundo pelo subsolador (em até 0,80 m) em combinação com a calagem adicional promoveu melhorias de até 0,40 m de profundidade no solo, favorecendo o crescimento do cafeeiro. No segundo estudo, foi investigada a relação entre os preparos de solo e a prática da calagem adicional em relação à qualidade física do Cambissolo e à proteção antioxitante do cafeeiro sob dois períodos (seco e úmido). O preparo em até 0,60 m sem o adicional de calagem mostrou vantagens, como agregação, menor resistência do solo à penetração, maior desenvolvimento radicular e menor armazenamento hídrico durante o período seco. Esse preparo também resultou em maior atividade enzimática do sistema antioxidante, com menor peróxido de hidrogênio e peroxidação lipídica, evidenciando sua eficiência na tolerância à seca por parte das plantas sob esta condição de preparo. O terceiro estudo utilizou a tomografia computadorizada de raios-X para quantificar as mudanças estruturais do Cambissolo decorrentes de diferentes estratégias de preparo do solo e seu impacto no crescimento do café. O preparo profundo com subsolador, aliado a correções químicas específicas, condicionou efeitos significativos em alterar efetivamente as características estruturais deste Cambissolo raso e naturalmente denso, promovendo o crescimento das plantas de café. Assim, os resultados dos três estudos destacam a importância da abertura profundo dos sulcos de plantio e a tomada de decisão no momento do preparo inicial do solo, especialmente com o uso do subsolador, a fim de se evitar perdas da qualidade físico-hídrica estrutural do Cambissolo. Desta forma, a abertura profunda do solo aliado a correções químicas adequadas, melhoram a qualidade físico-hídrica do Cambissolo e otimizam o desenvolvimento do cafeeiro. Essas estratégias mostram ser benéficas e portanto, essenciais para o sucesso do cultivo de café em solos com restrições, resultando em maior crescimento e melhor adaptação às condições de campo sob sequeiro.

Palavras-chave: Correção química profunda. Enzimas antioxidantes. NDVI. Resistência à penetração. Sistema radicular. Tomografia Computadorizada.

ABSTRACT

The demand for land for coffee cultivation has increased due to the popularity of this beverage, including in soils with physical and hydric restrictions, such as Cambisols. Although most plantations are in rainfed areas, management strategies to optimize soil water use are crucial. Investment in initial preparation technology, such as opening deep planting furrows, is essential to ensure long-term success and improve the physical-hydric quality of the soil. In this context, three studies were conducted in an experimental area of Cambisol in Nazareno, Minas Gerais, Brazil. Soil preparations are distinguished concerning the opening of the planting furrow: SP40 (up to 0.40 m through the furrower); SP60 (up to 0.60 m by Big Mix, soil homogenizer); SP80 (up to 0.80 m through Dreno, subsoiler) and distinguished in terms of chemical correction in depth by additional liming (SP60AL; SP80AL) or by mixing with gypsum, serpentinite and natural phosphate (SP40M; SP60M; SP80M). The first study analyzed the effects of different deep tillage strategies and chemical correction of the planting furrow on soil physical quality and growth of coffee plants over five years. The results showed that the preparation of the deep furrow by the subsoiler (up to 0.80 m) in combination with additional liming promoted improvements of up to 0.40 m in depth in the soil, favoring the growth of the coffee plant. The second study investigated the relationship between soil preparation and the practice of additional liming concerning the Cambisol's physical quality and the coffee plant's antioxidant protection under two periods (dry and wet). Up to 0.60 m tillage without additional liming showed advantages, such as aggregation, lower soil resistance to penetration, more remarkable root development, and less water storage during the dry period. This preparation also resulted in more significant enzymatic activity of the antioxidant system, with less hydrogen peroxide and lipid peroxidation, evidencing its efficiency in the drought tolerance of the plants under this preparation condition. The third study used X-ray computed tomography to quantify structural changes in the Cambisol resulting from different soil preparation strategies and their impact on coffee growth. Deep tillage with a subsoiler, combined with specific chemical corrections, conditioned significant effects in effectively changing the structural characteristics of this shallow and naturally dense Cambisol, promoting the growth of coffee plants. Thus, the results of the three studies highlight the importance of deep opening the planting furrows and decision-making at the time of initial soil preparation, especially with the use of a subsoiler, to avoid losses in the physical-hydric structural quality of the Cambisol. In this way, the deep opening of the soil, combined with adequate chemical corrections, improves the Cambisol's physical-hydric quality and optimizes the coffee plant's development. These strategies are beneficial and, therefore, essential for the success of coffee cultivation in restricted soils, resulting in more significant growth and better adaptation to field conditions under rainfed conditions.

Keywords: Antioxidant enzymes. Computed tomography. Deep chemical correction. NDVI. Penetration resistance. Root system.

SUMMARY

PRIMEIRA PARTE

INTRODUÇÃO GERAL

O Brasil é uma potência mundial na indústria agroalimentar, enfrentando desafios associados à sustentabilidade na cadeia produtiva. Nesse contexto, é necessário inovação no âmbito do agronegócio e, portanto, tomar decisões que priorizem ações para superar limitações, especialmente na indústria cafeeira. O Brasil é considerado o maior exportador e o segundo maior consumidor de café, detém um terço da produção mundial, tornando-se o principal produtor a nível global em relação a este grão (GUIMARÃES et al., 2022; TORGA et al., 2020).

De acordo com a Companhia Nacional de Abastecimento, a área total destinada à cafeicultura no Brasil em 2023 foi de 2,25 milhões de hectares, representando um aumento de 0,3% em relação à safra anterior, devido à abertura de novas áreas. A produção cafeeira da variedade Arábica, mais consumida mundialmente, corresponde a 69,3% do total, com uma estimativa de colheita de 37,93 milhões de sacas, enquanto a variedade Conilon representa 16,81 milhões de sacas (CONAB, 2023). O estado de Minas Gerais possui a maior área cultivada de café Arábica no Brasil, com mais de 1.316,59 mil hectares, o que corresponde a 70% da área total destinada à produção nacional (CONAB, 2022).

A atividade cafeeira, pode ser muito afetada por adversidades climáticas que resultem em déficit hídrico (SANTOS et al., 2014; SILVA et al., 2015). Segundo a CONAB (2022) e como observado por COLTRI et al. (2019), intempéries climáticas e má distribuição de chuvas são os principais fatores contribuintes para a perda de produtividade desta cultura. Desta forma, como agravante, o déficit hídrico e prolongamento de período de seca tem sido observado de forma recorrente para uma das maiores regiões produtoras do Estado mineiro, (ALVARENGA et al., 2018). Assim como enfatizado para o período de safra 2021/2022 (CONAB, 2022; CONAB, 2023), o que pode reduzir a aptidão agrícola para a cafeicultura na tradicional região do Estado mineiro (TAVARES et al., 2018).

Nesse contexto, é urgente a necessidade de aprimorar o conhecimento sobre o uso do solo na agricultura (POPPIEL et al., 2018), gestão da água e dos fertilizantes (CHEN et al., 2019). Assim como melhoramento genético (CORONA-LOPEZ et al., 2019) e entendimento sobre aspectos fisiológicos desta cultura (WEIGAND; KEMNA, 2017; 2019), incluindo estudos sobre atividade do sistema antioxidante como uma ferramenta eficaz para avaliar o estresse das plantas (GARCIA et al., 2019).

Devido à expansão contínua da atividade cafeeira (CONAB, 2023), muitas vezes a abertura de novas áreas ocorre em zonas marginais para a agricultura (BARBOSA et al., 2020), sendo observado limitações topográficas e pedológicas (SERAFIM et al., 2011). Nestes ambientes, destaca-se a presença de Cambissolos, que mesmo pouco desenvolvidos em termos de profundidade (MEDEIROS et al., 2013), já representam cerca de 10% das áreas cafeeiras em Minas Gerais (BERNARDES et al., 2012). Essa classe de solo ocupa aproximadamente 10,5 milhões de hectares, correspondendo a cerca de 18% da área total deste estado (AMARAL et al., 2004; OLIVEIRA et al., 2019).

Com a finalidade de aumentar a produtividade e manter competitividade no mercado interno e externo, os cafeicultores estão cada vez mais conscientes da necessidade de melhorias nas lavouras, incluindo preparo eficiente juntamente com a conservação do solo e da água (SERAFIM et al., 2011; SERAFIM et al., 2013a e b; CARDUCCI et al., 2014; SILVA et al., 2014; CARDUCCI et al., 2015a e b; SILVA et al., 2016a e b; SILVA et al., 2019; CARDUCCI et al., 2021). Uma dessas melhorias, está associada à prática da abertura profunda do sulco de plantio no momento da implantação da lavoura cafeeira, visando construir um bom perfil de solo, maximizando o desenvolvimento radicular e por tanto a qualidade físico-hídrica do solo (BARBOSA et al., 2020; SILVA et al., 2021), intencionando a sustentabilidade do sistema de produção (ARAÚJO JUNIOR et al., 2008).

Neste sentido, práticas de preparo profundo do solo realizadas com maquinários específicos para a cafeicultura visam melhorar o estabelecimento desta cultura principalmente durante os primeiros anos de cultivo (BARBOSA et al., 2020; SILVA et al., 2021). Essas práticas promovem o rompimento e afrouxamento do solo, permitindo melhor exploração do subsolo pelas raízes e maior absorção de água, o que impacta diretamente na produção do cafeeiro (AKINCI et al., 2004; MEDEIROS et al., 2013; QUEREJETA et al., 2001; CAI et al., 2014; SANTOS et al., 2014; RENA; MAESTRI, 1986). No entanto, é importante ressaltar que, ao longo do tempo, solos submetidos a esse tipo de preparo podem passar por processo de reconsolidação, o que pode levar à perda e o desaparecimento das melhorias iniciais promovidas pelos maquinários (DRESCHER et al., 2011; REICHERT et al., 2017), principalmente em Cambissolos preparados em profundidade (SILVA et al., 2021).

A correção química em profundidade no solo também pode ser proposta como prática importante, visando melhorias do perfil de solo como um todo para maximizar o desenvolvimento radicular, refletindo em aumento da disponibilidade de água e nutrientes para as plantas (INFORZATO; REIS, 1963; CARVALHO-PUPATTO et al., 2003; ARAÚJO JUNIOR et al., 2008; RAMOS et al., 2013; SILVA et al., 2015; CAVALCANTE et al., 2019;

SILVA et al., 2019; BARBOSA et al., 2020).

Manejos que otimizem a exploração do perfil de solo pelas raízes é crucial devido à ocorrência de períodos de estiagem (seca), já relatados (EVANGELISTA et al., 2002; SILVA et al., 2015). Assim, a resolução dessa problemática, ao associar às condições de sequeiro imposta em sua maioria pela atividade cafeeira no Brasil e bem como submetida em regiões como a do Cerrado, onde há menor concentração de chuvas juntamente com períodos de seca severos e extensos, apresenta grande relevância, considerando os empregos gerados, o papel do café no PIB nacional (COLTRI et al., 2019) e seu impacto na segurança alimentar (DRABO, 2017).

Desta forma, é essencial realizar estudos que avaliem os efeitos de manejo do solo a longo prazo, o que pode ser feito a partir de indicadores da qualidade físico-hídrica e utilizando tecnologias robustas como a análise da tomografia computadorizada associada à ciência do solo (CARDUCCI et al., 2014a, 2014b, 2015a, 2017, 2022). Essa tecnologia tem por intuito identificar os reais benefícios promovidos a partir das diferentes formas de preparo ou até mesmo identificar condições inadequada devido a tomada de decisões incorretas no momento do preparo inicial do solo. Esses estudos devem estar integrados ao estabelecimento adequado das plantas de café no campo (BARBOSA et al., 2020), principalmente objetivando crescimento, desenvolvimento e vigor vegetativo desta cultura.

Em regiões como o Cerrado, onde ocorrem limitações climáticas expressivas, é necessário adotar estratégias de preparo do solo para melhor auxiliar na condução das culturas visando contornar condições de estresse abiótico por efeitos do déficit hídrico. Desta forma, o cultivo de cafeeiros requer uma especial atenção nestas regiões, visto o longo tempo desta cultura no campo e seu importante estabelecimento. Neste contexto, os cafeicultores devem planejar cuidadosamente a forma como o solo será preparado para evitar perdas da qualidade físico-hídrica estrutural e promover uma maior longevidade e sustentabilidade de toda a cadeia produtiva desta cultura.

REFERÊNCIAS

ALVARENGA, L.A., DE MELLO, C.R., COLOMBO, A., CHOU, S.C., CUARTAS, L.A., VIOLA, M.R. Impacts of climate change on the hydrology of a small Brazilian headwater catchment using the Distributed Hydrology-Soil-Vegetation Model. **American Journal of Climate Change**, v.7, p.355, 2018.

AKINCI, I.; CAKIR, E.; TOPAKCI, M.; CANAKCI, M.; INAN, O. The effect of subsoiling on soil resistance and cotton yield. **Soil and Tillage Research**, v.77, p.203-210, 2004.

AMARAL, F. C. S.; SANTOS, H. G.; ÁGLIO, M. L. D.; DUARTE, M. N.; PEREIRA, N. R.; OLIVEIRA, R. P.; CARVALHO JÚNIOR, W. **Mapeamento de solos de aptidão agrícola das terras do estado de Minas Gerais**. Rio de Janeiro: Embrapa Solos, 2004. 97p.

ARAÚJO JUNIOR, C. F.; DIAS JÚNIOR, M. S.; GUIMARÃES, P. T. G.; PIRES, B. S. Resistência à compactação de um Latossolo cultivado com cafeeiro, sob diferentes sistemas de plantas invasoras. **Revista Brasileira de Ciência do Solo**, v.32, p.25-32, 2008.

BARBOSA, S. M.; OLIVEIRA, G. C. de.; SILVA, B. M.; BENEVENUTE, P. A. N.; SILVA, R. F. da.; CURI, N.; MORETTI, B. da. S.; SILVA, S. H. G.; NORTON, L. D.; PEREIRA, V. M. Deep furrow and additional liming for coffee cultivation under first year in a naturaly dense inceptisol. **Geoderma**, v.357, p.113934, 2020.

BERNARDES, T.; MOREIRA, A. M.; ADAMI, M.; RUDORFF, B.; FRIEDRISH, T. Diagnóstico físico-ambiental da cafeicultura no estado de Minas Gerais – Brasil. **Coffee Science**, Lavras, v. 7, n. 2, p. 139-15, 2012. Disponível em: http://www.sbicafe.ufv.br:80/handle/123456789/7910. Acesso em: 10 jan. 2021.

CAI, H.; MA, W.; ZHANG, X.; PING, J.; YAN, X.; LIU, J.; YUAN, J.; WANG, L.; REN, J. Effect of subsoil tillage depth on nutrient accumulation, root distribution, and grain yield in spring maize. **The Crop Journal**, v2, 297–307, 2014.

CARDUCCI, C. E.; OLIVEIRA, G. C.; LIMA, J. M.; ROSSONI, D. F.; COSTA, A. L.; OLIVEIRA, L. M. Distribuição espacial das raízes de cafeeiro e dos poros de dois Latossolos sob manejo conservacionista. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.18, p.270-278, 2014.

CARDUCCI, C. E.; OLIVEIRA, G. C.; CURI, N.; HECK, R. J.; ROSSONI, D. F. F.; CARVALHO, T. S. S.; COSTA, L. L. Gypsum effects on the spatial distribution of coffee roots and the pores system in oxidic Brazilian Latosol. **Soil and Tillage Research**, v.145, p.171-180, 2015a.

CARDUCCI, C. E.; OLIVEIRA, G. C.; OLIVEIRA, L.; BARBOSA, S. M.; SILVA, E. A.; Retenção de água do solo sob sistema conservacionista de manejo com diferentes doses de gesso. **Revista de Ciências Agrárias**, v.58, n.3, p.284-291, 2015b.

CARDUCCI, C. E.; OLIVEIRA, G. C.; ZEVIANI, W. M.; LAUREANO, H. A.; BARBOSA, S. M.; SEVERIANO, E. C.; CURI, N. Preconsolidation stress of gibbsitic and kaolinitic Oxisols under a multipractice conservationist coffee system. **Semina: Ciências Agrárias**, v. 42, n. 3, p. 1049-1068, 2021.

CARDUCCI, C. E.; PINTO, L. C.; BARBOSA, S. M.; COSTA, J. C.; ZINN, Y. L.; HECK, R. J. Micromorfologia e tomografia de raios-x: porosidade de um Latossolo gibbsítico sob sistema multi-práticas de manejo cafeeiro. **Recima21-Revista Científica Multidisciplinar**, v.3, p.e361520–e361520, 2022.

CARDUCCI, C. E.; ZINN, Y. L.; ROSSONI, D. F.; HECK, R. J.; OLIVEIRA, G. C. Visual analysis and X-ray computed tomography for assessing the spatial variability of soil structure in a cultivated Oxisol. **Soil and Tillage Research**, v.173, p.15-23, 2017.

CARVALHO-PUPATTO, J. G.; BÜLL, L. T.; CRUSCIOL, C. A. A.; MAUAD, M.; SILVA, R. H. Efeito de escória de alto forno no crescimento radicular e na produtividade de arroz. **Pesquisa Agropecuaria Brasileira**, v.38, p.1323-1328, 2003.

CAVALCANTE, D. M.; CASTROA, M. F. de; CHAVES, M. T. L.; SILVA, I. R. da; OLIVEIRA T. S. de. Effects of rehabilitation strategies on soil aggregation, C and N distribution and carbon management index in coffee cultivation in mined soil. **Ecological Indicators**, v.107, p.105668, 2019.

CHEN, B.; GARRÉ, S.; LIU, H.; YAN, C.; LIU, E.; GONG, D.; MEI, X. Two-dimensional monitoring of soil water content in fields with plastic mulching using electrical resistivity tomography. **Computers and Electronics in Agriculture**, v.159, p.84-91, 2019.

COLTRI, P. P.; PINTO, H. S.; GONÇALVES, R. R. V.; ZULLO JUNIOR, J.; DUBREUIL V. Low levels of shade and climate change adaptation of Arabica coffee in southeastern Brazil. **Heliyon**, v.5, n.2, p.01263, 2019.

CONAB, Companhia Nacional de Abastecimento. **Acompanhamento da safra brasileira, café, safra 2023, 2º levantamento, Maio de 2023.** 10, 1–45. Disponível em: https://www.conab.gov.br/info-agro/safras/cafe. Acesso em: 23 jun 23. 2023.

CONAB, Companhia Nacional de Abastecimento. **Acompanhamento da safra brasileira, café, safra 2022, 4º levantamento, Dezembro de 2022.** 9, 1–53. Disponível em: https://www.conab.gov.br/info-agro/safras/cafe/boletim-da-safra-de-cafe Acesso em: 10 abr. 2022.

CORONA-LOPEZ, D. D. J.; SOMMER, S.; ROLFE, S. A.; PODD, F.; GRIEVE, B. D.; Electrical impedance tomography as a tool for phenotyping plant roots. **Plant Methods**, v.15, n.49, 2019.

DRABO, A. Climate change mitigation and agricultural development models: primary commodity exports or local consumption production? **Ecological Economics**, v.137, p.110-125, 2017.

DRESCHER, M. S.; ELTZ, F. L. F.; DENARDIN, J. E.; FAGANELLO, A. Persistência do efeito de intervenções mecânicas para a descompactação de solos sob plantio direto. **Revista Brasileira de Ciência do Solo**, v.35, p.1713–1722, 2011.

EVANGELISTA, A. W. P.; CARVALHO, L. G. DE; SEDIYAMA, G. C. Zoneamento climático associado ao potencial produtivo da cultura do café no Estado de Minas Gerais. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.6, p.445-452, 2002.

GARCIA, F. H. S.; MATUTE, A. F. M.; SILVA, L. C.; SANTOS, H. R. B.; BOTELHO, D. S.; RODRIGUES, M.; BARBOSA, J. P. R. A. D. Análise fisiológica em mudas de cafeeiro com cercosporiose submetida a diferentes lâminas de irrigação. **Summa Phytopathologica**, v. 45, n. 1, p. 83-88, 2019.

GUIMARÃES, Y. M.; EUSTACHIO, J. H. P. P.; LEAL FILHO, W.; MARTINEZ, L. F.; DO VALLE, M. R.; CALDANA, A. C. F. Drivers and barriers in sustainable supply chains: The case of the Brazilian coffee industry. **Sustainable Production and Consumption**, v.34, p.42-54, 2022.

INFORZATO, R.; REIS, A. J. Estudo comparativo do sistema radicular dos cafeeiros Bourbon amarelo e Mundo Novo. **Bragantia**, v.22, p.74-750, 1963.

MEDEIROS, J. C.; FIGUEIREDO, G. C.; MAFRA, Á. L.; ROSA, J. D.; YOON, S. W. Deep subsoiling of a subsurface-compacted typical hapludult under citrus orchard. **Revista Brasileira de Ciência do Solo**, v.37, p.911-919, 2013.

OLIVEIRA, G. C.; SILVA, B. M.; CARDUCCI, C. E.; SILVA, S. H. G.; SERAFIM, M. E.; BARBOSA, S. M.; SILVA, E. A.; MELO, L. B. B.; BENEVENUTE, P. A. N. **Melhoria físico-hídrica do ambiente radicular do cafeeiro em condições de sequeiro e implicações no uso da água**. In Tópicos em Ciência do Solo; Severiano, E.C., Moraes, M.F., Paula, A.M., Eds.; Sociedade Brasileira de Ciência do Solo (SBCS), Viçosa, p.70-140, 2019.

POPPIEL, R.R.; LACERDA, M.P.C.; OLIVEIRA JUNIOR, M.P. DE. DEMATTÊ, J.A.M.; ROMERO, D.F.; SATO, M.V.; ALMEIDA JÚNIOR, L.R. DE. CASSOL, L.F.M. Surface Spectroscopy of Oxisols, Entisols and Inceptisol and Relationships with Selected Soil Properties. Revista Brasileira de Ciencência do Solo, v.42, p.160-519, 2018.

QUEREJETA, Â., ROLDA, A., ALBALADEJO, J., CASTILHO, V. Soil water availability improved by site preparation in a Pinus halepensis afforestation under semiarid climate. **Forest Ecology and Management**, v.149, p.115–128, 2001.

RAMOS, B.Z., TOLEDO, J.P.V.F., LIMA, J.M., SERAFIM, M.E., BASTOS, A.R.R., GUIMARÃES, P.T.G., COSCIONE, A.R. Doses de gesso em cafeeiro: influência nos teores de cálcio, magnésio, potássio e pH na solução de um Latossolo Vermelho distrófico. **Revista Brasileira de Ciência do Solo**, v.37, p.1018-1026, 2013.

REICHERT, J. M.; BRANDT, A. A.; RODRIGUES, M. F.; VEIGA, M.; REINERT, D. J. Is chiseling or inverting tillage required to improve mechanical and hydraulic properties of sandy clay loam soil under long-term no-tillage? **Geoderma**, v.301, p.72–79, 2017.

RENA, A. B.; MAESTRI, M. Fisiologia do cafeeiro. In: RENA, A. B.; MALAVOLTA, E.; ROCHA, M.; YAMADA, T. (Eds.). Cultura do cafeeiro: fatores que afetam a produtividade. Piracicaba: **Potafos**, p.13-86, 1986.

SANTOS, W. J. R.; SILVA, B. M.; OLIVEIRA, G. C.; VOLPATO, M. M. L.; LIMA, J. M.; CURI, N.; MARQUES, J. J. Soil moisture in the root zone and its relation to plant vigor assessed by remote sensing at management scale. **Geoderma**, v.221–222, p.91–95, 2014.

SERAFIM, M. E.; OLIVEIRA, G. C.; LIMA, J. M.; SILVA, B. M.; ZEVIANI, W. M.; LIMA, V. M. P. Disponibilidade hídrica e distinção de ambientes para cultivo de cafeeiros. **Revista Brasileira de Engenharia Agrícola e Ambiental**. Campina Grande, v.17, n.4, p.362-370, 2013a.

SERAFIM, M. E.; OLIVEIRA, G. C.; OLIVEIRA, A. S.; LIMA, J. M.; GUIMARÃES, P. T. G.; COSTA, J. C. Sistema conservacionista e de manejo intensivo do solo no cultivo de cafeeiros na região do Alto São Francisco, MG: Um estudo de caso. **Bioscience Journal**, v.27, p.964-977, 2011.

SERAFIM, M. E.; OLIVEIRA, G. C.; VITORINO, A. C. T.; SILVA, B. M.; CARDUCCI, C. E. Qualidade física e intervalo hídrico ótimo em Latossolo e Cambissolo, cultivados com cafeeiro, sob manejo conservacionista do solo. **Revista Brasileira de Ciência do Solo**, v.37, n.3, p.733-742, 2013b.

SILVA, B. M.; SANTOS, W. J. R.; OLIVEIRA, G. C.; LIMA, J. M. DE; CURI, N., MARQUES, J. J. G. S. M. Soil misture space-time analysis to support improved crop management. **Ciência e Agrotecnologia**, v.39, p.39-47, 2015.

SILVA, B. M.; OLIVEIRA, G. C. de.; SERAFIN, M. E.; SILVA, E. A. da.; GUIMARAES, P. T. G.; MELO, L. B. B.; NORTON, L. D.; CURI, N. Soil moisture associated with least limiting water range, leaf water potential, initial growth and yield of coffee as affected by soil management system. **Soil and Tillage Research**, v. 189, p. 36–43, 2019.

SILVA, É. A.; DE OLIVEIRA, G. C.; CARDUCCI, C. E.; SILVA, B. M.; SERAFIM, M. E. Aggregates morphometry of a Inceptisol under conservationist system. **Semina: Ciências Agrárias**, v.37, p.1165-1176, 2016b.

SILVA, É. A.; OLIVEIRA, G. C.; CARDUCCI, C. E.; LIMA, J. M.; MELO, L. B. B.; BENEVENUTE, P. A. N. Stability of soil aggregates in Latosols and Cambisols via standard method and sonification. **African Journal of Agricultural Research**, Essex, v.11, n.39, p. 38943903, 2016a.

SILVA, É. A.; OLIVEIRA, G. C.; SIVA, B. M.; CARDUCCI, C. E.; AVANZI, J. C.; SERAFIM, M. E. Aggregate stability by the high energy moisture characteristic method in an Oxisol under differentiated management. **Revista Brasileira de Ciência do Solo**, v.38, n.5, p.1633-1642, 2014.

SILVA, R. F.; SEVERIANO, E. C.; OLIVEIRA, G. C.; BARBOSA, S. M.; PEIXOTO, D. S.; TASSINARI, D.; SILVA, B. M.; SILVA, S. H. G.; DIAS JÚNIOR, M. S.; FIGUEIREDO, T. A. F. R. Changes in soil profile hydraulic properties and porosity as affected by deep tillage soil preparation and Brachiaria grass intercropping in a recent coffee plantation on a naturally dense Inceptisol. **Soil and Tillage Research**. 213, 105127, 2021.

TAVARES P. S; GIAROLLA A.; CHOU S. C.; SILVA, A. J. P.; LYRA, A. A. Climate change impact on the potential yield of Arabica coffee in southeast Brazil. **Regional Environmental Change**, v.18, p.873-883, 2018.

TORGA, G. N.; SPERS, E. E.; **Perspectives of global coffee demand. Coffee Consumption**

and Industry Strategies in Brazil, p.21-49, 2020.

WEIGAND, M.; KEMNA, A. Imaging and functional characterization of crop root systems using spectroscopic electrical impedance measurements. **Plant and Soil**, v.435, p.201-224, 2019.

WEIGAND, M.; KEMNA, A. Multi-frequency electrical impedance tomography as a non-invasive tool to characterize and monitor crop root systems. **Biogeosciences**, v.14, p.921-939, 2017.

SECOND PART - MANUSCRIPTS

MANUSCRIPT – I

(Manuscript formatted according to Soil and Tillage Research Journal guidelines)

Deep soil tillage in the coffee planting furrow has long-lasting benefits for improving soil physical quality and enhancing plant vigor in dense soils

Abstract: Coffee adapts to various environments through soil preparation. Drought effects are critical in dense soils, but preparation strategies like deep furrow preparation combined with additional liming can improve soil quality and mitigate drought during initial coffee crop establishment. However, the impacts of the initial preparer in the medium to long term are scarce. This study aims to assess the five-year effects of different deep tillage strategies and chemical fertility improvement of the planting furrow on soil physical quality and plant growth under Cambisol with coffee cultivation. The field experiment was conducted on a commercial farm in Nazareno, Minas Gerais, Brazil, in a Cambisol area with a clay loam texture. A randomized block design experiment was performed with three blocks, and the following five soil preparations were tested: SP40: soil preparation with a furrower was used to open the planting furrow at 0.40 m depth with conventional fertilization; SP60: Big Mix (Soil homogenizer) was applied at 0.60 m with conventional fertilization and with chemical amendments by additional liming (SP60AL); SP80: Soil homogenizer was employed at 0.60 m, followed by a Dreno (subsoiler) at 0.80 m with conventional fertilization and with additional liming (SP80AL). These soil preparations were compared to an area apart from the experimental site under native savannah vegetation from the Cerrado biome (Natural). Undisturbed samples were collected at depths of 0.00-0.05, 0.15-0.20, 0.35-0.40, 0.55-0.60, 0.65-0.70, and 0.75-0.80 m five years after the initial soil preparation. In these samples, physical quality indicators were investigated along with the correlation of plant measurements (stem diameter - SD, plant height - PH, and normalized difference vegetation index - NDVI). A comparison between these soil preparation strategies at the end of the 5th cycle was studied to test the long-term effect of the deep tillage with the data of these same preparations at the end of the 2nd cycle. Analysis of variance and the Scott-Knott and Dunnett tests ($p < 0.05$) were applied to analyze the data. After five years of soil preparation, significant improvements up to a depth of 0.40 m were due to soil homogenization, subsoiling, and additional liming. This preparation strategy promoted lower bulk density, favoring larger pores, and reducing tiny pores, enhancing water retention and its availability to plants. Additional limestone between 0.20 and 0.60 m depth improves the SD, PH, and NDVI, helping mitigate drought impacts. Nevertheless, indications of induced compaction at the bottom of the furrow during the initial soil preparation persist. Over time, this compaction reduced soil physical quality between depths of 0.60 m to 0.70 m. At 0.80 m depth, there are indications of inefficiency or disappearance of the subsoiler effects, indicating soil reconsolidation after tillage by the end of the 5th cycle compared to the results of the 2nd cycle from this same coffee area. Therefore, effective preparation practices for deep tillage improve the soil physical quality of naturally dense soil, mitigating drought effects but requiring careful planning and implementation.

Keywords: Additional liming; NDVI; Physical quality indicators; Soil structure; Subsoiling

1. Introduction

Coffee is the most consumed beverage globally, with Brazil as the largest producer and second-largest consumer (Torga et al., 2020). Other major coffee-producing countries include Vietnam, Colombia, Indonesia, and Ethiopia (Ayele et al., 2021). In Brazil, Minas Gerais has the largest cultivated area of *Coffea arabica* L., covering over 1,316.59 thousand hectares, representing almost 70% of the country's total coffee cultivation area (Conab, 2022). Agriculture in Minas Gerais, particularly in Campo das Vertentes mesoregion, belonging to the Cerrado biome, faced challenges due to climate change and a reduction in rainfall related to rainfed conditions, which was significantly affected by prolonged drought periods (Conab, 2023).

Coffee cultivation is primarily carried out on small rural properties, and it is frequently established in pedological environments considered marginal for agriculture, mainly in undulating mountainous relief and shallow soil depth (Barbosa et al., 2020; Silva et al., 2021). These environments frequently include Cambisol, the second-most extensive soil type in the world, comprising 12% of the total continental area, 1.5 billion hectares (FAO et al., 2001). In Minas Gerais, this soil covers around 10.5 million hectares or about 18% of the entire area of this state, contributing to approximately 10% of the coffee-growing regions (Oliveira et al., 2019). However, limitations like lower plant available water and air capacity are caused by high Bulk density (Reynolds et al., 2009), which is linked to the dense layer and the result of changes in soil physical properties. This scenario can occur particularly in soils with high silt content (Ghosh and Daigh, 2020), and coffee's potential for production can be reduced (Silva et al., 2021).

Coffee producers are increasingly aware of the need for improvements in soil preparation, integrating soil and water conservation practices for soil physical quality improvement, achieving higher crop yields, and remaining competitive in the international market (Carducci et al., 2014; Carducci et al., 2015a e b; Silva et al., 2016; Barbosa et al., 2020; Silva et al., 2021). In this approach, the studies aiming plant water stress reduction, water economy, and improving agricultural production in climate change figure among the United Nations (UN) Sustainable Development Goals (SDGs) for 2030, specifically in 2.12 and 13 SDG: zero hunger promoting sustainable agricultural; responsible consumption, production, and climate action (United Nations, 2021). This way, the research within the context above comprises practical measures to achieve these goals.

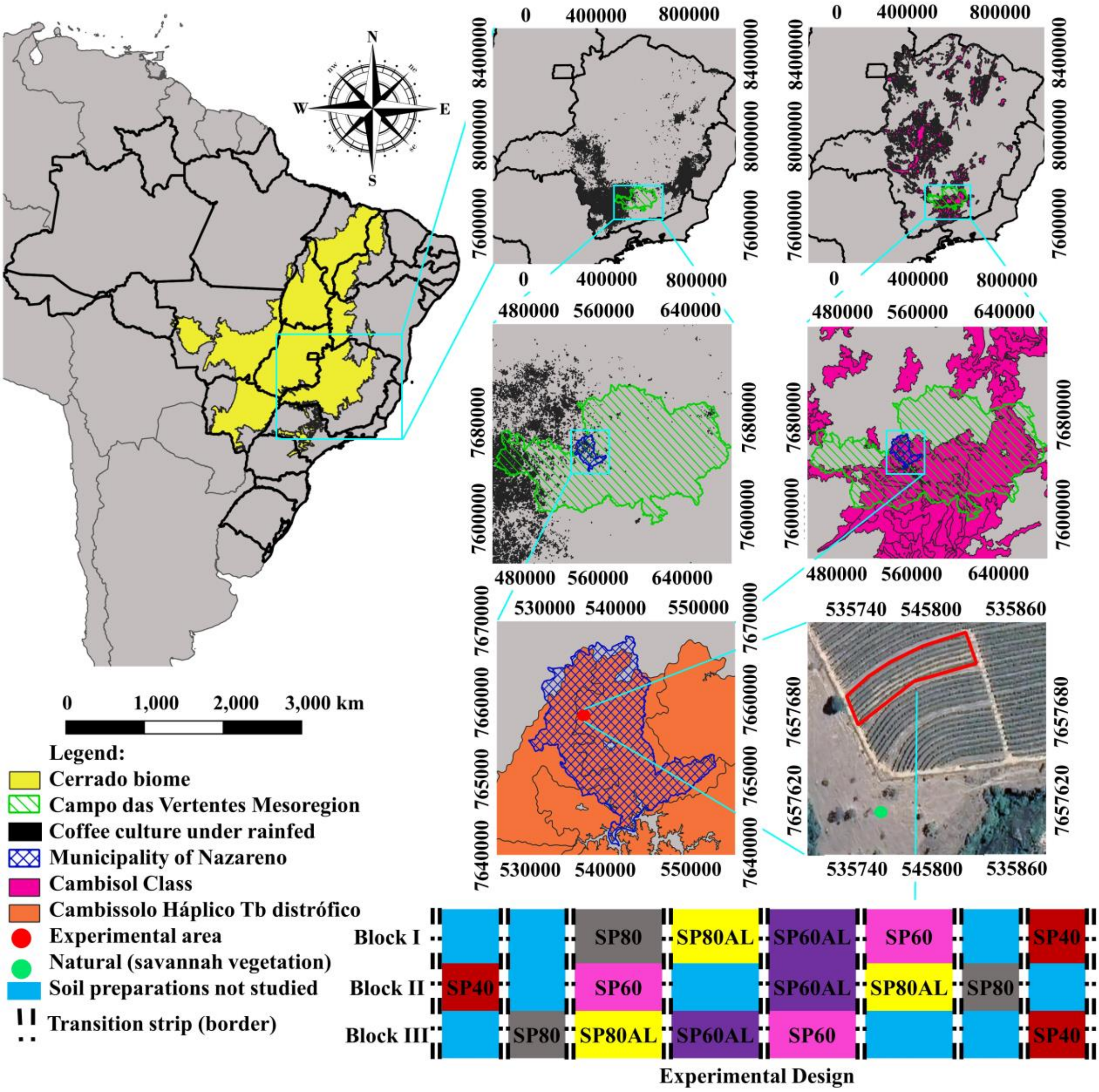
Deep tillage strategies have been carried out to improve crop root development (Azevedo et al., 2022). For coffee crops, specific machinery at both 0.60 m and 0.80 m depths have been tested (Barbosa et al., 2020; Silva et al., 2021). This system promotes soil rupture and loosening, improving root system exploration of the subsoil (Santos et al., 2014), resulting in better water uptake (Silva et al., 2015), and positively impacting coffee yield. However, soils that machines have turned over might exhibit improvements initially (Reichert et al., 2017; Azevedo et al., 2022), but these benefits may fade over time due to the process of soil reconsolidation (Drescher et al., 2011; Nunes et al., 2014; Ghosh and Daigh, 2020). As a result, it should be noted the effectiveness of tillage systems affect the intrinsic attributes of the soil, such as its natural reconsolidation, since the response to different tillage systems and their effects on structural quality depends on the soil class (Azevedo et al., 2022). Thus, this process can occur in Cambisol, exposed to deep tillage preparation (Silva et al., 2021), justifying the evaluation of the effects of this deep preparation of the planting furrow over time.

This research hypothesizes that the impacts of deep tillage strategies in the naturally dense soil will continue to be seen when coffee plants reach their productive age (5th cycle) and that the effects vary depending on the soil tillage depth, preparation, and additional liming. Consequently, the initial soil preparation has a continued positive impact on soil structure, directly influencing coffee plants' growth and response to their stem diameter, height, and plant vigor. Therefore, this study aims to assess the efficacy of various deep tillage strategies in mitigating the adverse effects of the natural dense layer in Cambisol five years after the establishment of the coffee crop.

2. Material and Methods

2.1. Site of Study

The experiment was carried out in a commercial farm coffee production located in the Nazareno municipality, Minas Gerais state, Brazil, with geographical coordinates latitude 21° 10' 52″ S and longitude 44° 39′ 04″ W (Figura 1) at an average altitude of 935 m. Pasture originally covered the area before introducing coffee (historical context of the experimental area). The soil in the site study was classified as Cambissolo Háplico Tb distrófico following the Brazilian Soil Classification System (Santos et al., 2018), corresponding to Typic Hapludept in Soil Taxonomy (Soil Survey Staff, 2014) and Dystric Cambisol (WRB, 2014) – official classification adopted in the present study –, presenting clay loam texture for horizons A and Bi (Figure 2). Pelitic rocks and quartzite on granite-gneiss are examples of the parent material (Horta et al., 2009), with chemical and physical characterization of the soil before the installation of the experiment presented in table 1. The local climate is Cwb, according to Köppen (1936) (Figure 1), a humid temperate climate with dry winter and moderately hot summer and an average annual temperature of 18.5°C. The rainy season is concentrated between November and March, with a yearly average of 1350 mm.



Block I	🟦	🟦	SP80	SP80AL	SP60AL	SP60	🟦	SP40
Block II	SP40	🟦	SP60	🟦	SP60AL	SP80AL	SP80	🟦
Block III	🟦	SP80	SP80AL	SP60AL	SP60	🟦	🟦	SP40

Figure 1. Location and design of the site of study in UTM zones. SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler.

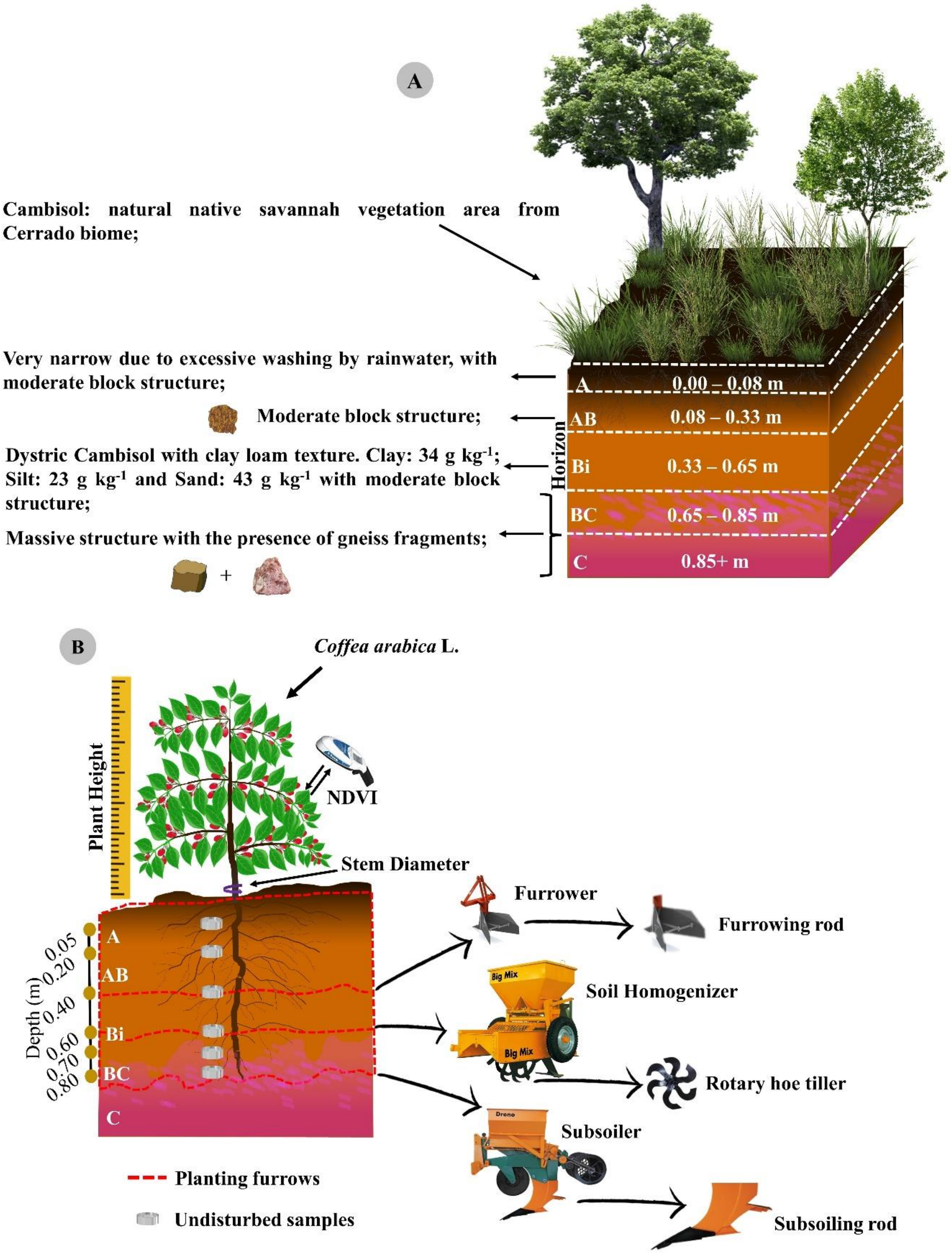


Figure 2. A: Schematic representation of the Cambisol profile under natural Cerrado savannah vegetation and its main pedological characteristics; B: Representation of the different soil preparations with the different agricultural implements used for the opening of the planting furrow under the coffee crop in the experimental area ally with the collection of

samples with preserved structure in the planting furrow area to evaluate the physical quality indicators and the plant measurements (stem diameter, plant height, and NDVI – normalized difference vegetation index). Adapted from Silva et al. (2021).

Table 1. Mean values of soil fertility analyses and soil particle size distribution at the soil profile before planting the coffee crop in 2015.

Depth	pH	K	P	Na	Ca	Mg	Al	H+Al	SB	t	T	V	m	M.O.	P-Rem	Zn	Fe	Mn	Cu	B	S	Clay	Silt	Sand
(m)	(H_2O)	mg dm^{-3}		cmol$_c$ dm^{-3}								%		dag kg^{-1}	mg.l^{-1}	mg dm^{-3}						g kg^{-1}		
0.00-0.20	5.1	22.7	0.4	2.0	0.4	0.1	0.2	3.2	0.6	0.8	3.7	15.9	28.8	2.3	13.4	0.9	61.1	5.8	1.8	0.7	6.0	33	16	51
0.20-0.40	5.5	16.7	0.3	2.7	0.3	0.1	0.1	2.8	0.4	0.5	3.2	13.1	19.9	1.9	8.0	0.6	40.3	2.3	1.7	0.2	5.1	33	23	44
0.40-0.60	5.8	11.3	0.1	2.0	0.3	0.1	0.0	1.9	0.4	0.4	2.3	18.9	0.0	1.5	3.4	1.0	27.2	1.6	1.5	0.2	5.0	35	22	43
0.60-0.80	5.7	12.0	0.0	2.0	0.4	0.1	0.0	1.8	0.5	0.5	2.4	22.7	0.0	1.0	3.1	0.7	32.0	2.5	1.5	0.1	4.6	37	27	36

pH: hydrogen potential determined in water; OM: Organic Matter; SB: Sum of bases; t: effective cation exchange capacity; T: potential cation exchange capacity; m: aluminum saturation; V: Base saturation; P-Rem: Remaining phosphorus. Adapted from Barbosa et al. (2020).

2.2. Soil Preparation

The soil chemical correction was done following the soil properties determined in table 1 before the coffee planting. Sixty days before planting was applied 3 Mg ha^{-1} (1,5 g dm^{-3}) in the total area of dolomitic limestone (total neutralizing relative power of 87 %; CaO of 39.7 %; MgO of 13.38 %) was incorporated into the soil by harrow implement with twenty discs, cutting width of 0.35 m and tractor power on average 230 hp.

Five soil preparation, one traditional, two aiming at the deep opening of the planting furrow, and two aiming at chemical amendment, combined with opening the planting furrow in depth, were implemented in a homogeneous area aiming at planting the coffee crop. The applied preparations were furrower (SP40); soil homogenizer (SP60); soil homogenizer + additional liming (SP60AL); soil homogenizer + subsoiler (SP80) and soil homogenizer + subsoiler + additional liming (SP80AL).

The furrower implement was designed to create furrows using a furrowing rod at a width of 0.35 to 0.65 m, depth of 0.40 m, tractor power of 60 hp, and weight of approximately 105 kg. The Big Mix equipment homogenizes the soil due to the presence of the rotary hoe tiller and soil correction by coupling the fertilizer box with a volume of 270 dm^3. This equipment has preparation effectiveness at a width of 0.50 m, depth of 0.60 m, tractor power of 85 hp, requiring super-reduced gear, speed of 0.6 to 1 km per hour, and weight of 450 kg (Mafes, 2017). The Dreno agricultural tool was designed to eliminate the physical impediments of the soil in depth due to the presence of the subsoiling rod that has a preparation capacity of up to 0.90 m, but effectively in up to 0.80 m, tractor power above 180 hp at a speed of up to 6 km per hour and with a load capacity of 450 kg or 1.2 tons (Mafes, 2017). The furrows opened to a depth of 0.40 m were closed with a two-rod subsoiler, operating at 3 to 5 km per hour, after the furrower passed through. For furrows opened to depths of 0.60 and 0.80 m, the Big Mix equipment was responsible for closing the furrows with a specific attached tool.

All preparations got fertilization following the coffee-growing recommendations (Guimarães et al., 1999). However, exclusively SP60AL and SP80AL, in addition to the recommended fertilization for the coffee crop, received 200g of additional dolomitic limestone per linear meter of the furrow, calculated from data in table 1. This strategy's goal was to increase the base saturation of soil to 70 %, being this additional liming mixed and incorporated effectively from 0.20 to 0.60 m depth in each one by the soil homogenizer due to the presence of the rotary hoe tiller and the coupling fertilizer box as described in Mafes (2017). Topdressing fertilizations were used three times, the first being in February 2016, when 0.004 kg of N and K_2O was applied per plant, always considering the twenty-day interval to increase the efficiency of nitrogen use and reduce losses, mainly by leaching.

Considering the susceptibility of the Cambisol group under undulating relief to water erosion, conservation practices were adopted to mitigate its effects. The mechanical method of terracing and the vegetative method of cultivation of *Brachiaria decumbens* L. (*Syn. Urochloa*) between crop rows were employed in combination.

To comprehend the effects of soil preparations following the coffee plantation, particularly after the completion of the 2nd cycle in 2017 (Barbosa et al., 2020; Silva et al., 2021), a series of cultural treatments were implemented. These treatments aimed to facilitate optimal growth and development of coffee plants, including applying topdressing fertilizer. These interventions aimed to assess the subsequent impacts on soil quality and crop performance. For the 2018-2019 crop, 0.66 kg of liming followed by 0.062 kg of N and K_2O and 0.013 kg of P_2O_5 was applied per plant. However, for the 2019-2020 crop, only 0.049 kg of N and K_2O was given per plant, the crop year associated with evaluating this Cambisol under coffee growing (the end of the 5th cycle).

2.3. Experimental Arrangement

Randomized blocks in the experimental design comprised five soil preparer strategies (SP40, SP60, SP60AL, SP80, SP80AL). Each experimental plot consisted of crop strips 10.8 m wide and 84 m long (907.2 m^2), with a planting line (10.5 m) with fourteen plants for each soil preparation studied, with three replications (Figure 1). The Catuaí Vermelho - IAC 99 coffee cultivar (*Coffea arabica* L.) was planted in December 2015, with a spacing of 0.75 m between plants and 3.6 m between planting lines (3,703 plants ha^{-1}). In each experimental plot, one external row (left and right) and one row between each soil preparer inside the testing area (nine total) were considered borders (Figure 1). In these lines, no soil was collected, and no plant was evaluated to minimize environmental effects and interaction between plots. All data collection to assess the characterization of the physical properties of the soil by physical quality indicators was performed randomly in the central plot strips.

2.4. Soil sampling and analysis

Soil samples were collected in December 2020, at the end of the 5th coffee cycle, five years after implantation. The trenches for each soil preparation were opened at a 0.20 m distance from the plant's trunk to the trench wall for collecting samples in the coffee-growing area (Figures 1 and 2). Equal sampling was conducted for all soil preparations, ensuring a canopy projection of 0.80 m to cover the horizontal reach of a single coffee plant. Also, a native savannah vegetation area from the Cerrado biome (Natural) was sampled and used as a reference apart from the experimental site. Undisturbed soil samples within metallic cylinders (0.063 m in diameter and 0.025 m in height) were collected using an Uhland-type sampler at the following depths: 0.00-0.05; 0.15-0.20; 0.35-0.40; 0.55-0.60; 0.60-0.70; 0.75-0.80 m.

For each depth (six depths), soil preparation strategies (five prepares), and block (three replicates), one sample was taken, totaling 90 samples. In addition, for each one of the six depths studied, three samples were collected in the native vegetation area, totaling 18 samples. Therefore, six treatments were studied (SP40, SP60, SP60AL, SP80, SP80AL, and Natural), totaling 108 samples.

2.4.1. Soil pore size distribution

The undisturbed soil samples were saturated by capillarity using distilled water. After saturation, the samples were subjected to matric potentials (Ψ_m) of -2, -4, -6, -8, and -10 kPa, in suction units comped of Buchner funnels and Ψ_m of -33, -100, -500, and -1500 kPa in the Richards extractor (Klute, 1986). After reaching equilibrium, the samples were weighed and oven-dried at 105 - 110º C for 24 hours. Soil water content (θ) was calculated for each Ψ_m, and therefore soil water retention curves (WRCs) were fitted using van Genuchten (1980) model with restriction m= 1- 1/n (Mualem, 1976) with Soil Water Retention Curve (SWRC) software (Dourado Neto et al., 2000).

The pore size distribution was calculated from the WRCs using the mathematical expression proposed by Bouma (1973). Its classification, according to Carducci et al. (2015b) and Klein (1998), adapted the micromorphological criteria proposed by Bullock et al. (1985), as follows: large macropores (LMacro) (>147 µm); fine macropores (FMacro) (147-73 µm); large mesopores (LMeso) (73-49 and 49-29 µm); average mesopores (AMeso) (29-9 and 9-2.9 µm); fine mesopores (FMeso) (2.9-0.6 µm); micropores (Micro) (0.6-0.2 µm) and Criptopores (Cripto) (< 0.2 µm).

2.5. Soil physical quality indicators -SPQI

Table 2. Primary approaches for assessing soil physical quality indicators, described in Reynolds et al. (2009), with modifications for their application to Brazilian tropical soils.

Indicator	**Abbreviation**	**Equation**	**Limits**	**Classification**	**Meaning**	**Reference Author**
Plant Available Water Capacity	P_{AWC}	$P_{AWC} = \theta_{FC} - \theta_{PWP}$	$P_{AWC} > 0.20$ $m^3.m^{-3}$	Ideal	Maximum growth and root uptake.	(White, 2006; Cockroft; Olsson, 1997).
			$0.15 \leq P_{AWC} < 0.20$ m^3 m^{-3}	Good	-	(Warrick, 2002).
			$0.10 \leq P_{AWC} < 0.15$ m^3 m^{-3}	Limited	-	
			$P_{AWC} < 0.10$ m^3 m^{-3}	Poor	-	
(θ_{PWP}): Permanent wilting point, θ volumetric water content at Ψ_m -1500 kPa; θ_{FC}: Volumetric water content at field capacity estimated by the moisture at the inflection point (θ_i) of the WRCs (Andrade and Stone, 2011) as suggested by Ferreira and Marcos (1983) for tropical soils and calculated according to Dexter and Bird (2001).						
Relative Field Capacity	RFC	$RFC = \frac{\theta i}{\theta s}$	$0.6 \leq RFC \leq 0.7$	-	Maximization in microbial production of nitrate and promote crop yield.	(Reynolds et al., 2009; Doran et al., 1990).
			$RFC < 0.6$	-	Soil water limitation (reduces nitrate production (affecting crop growth).	(Doran et al., 1990).
			$RFC > 0.7$	-	Soil limitation for aeration (affecting crop growth).	
θ_S: volumetric water content (m^3 m^{-3}) at saturation (Ψ_m 0 kPa).						
Air Capacity	AC	$AC = \theta_S - \theta_i$	$AC \geq 0.10$ m^3 m^{-3}	-	Minimum susceptibility to aeration deficit that harms the crop or reduces the root zone yield.	(Reynolds et al., 2009; White, 2006).

Macroporosity	P_{MAC}	$P_{MAC} = \theta_{S} - \theta_{6kPa}$	$0.05 \leq P_{MAC} < 0.10$ m^3 m^{-3}; Average: $P_{MAC} \geq 0.07$ m^3 m^{-3}	Ideal	Soil's ability to drain excess water and facilitate root proliferation quickly.	(Dexter et al., 2008; Reynolds et al., 2008; Drewry et al., 2001; Drewry; Paton, 2005).
			$P_{MAC} \leq 0.04$ m^3 m^{-3}	Critical	Soil degradation by compaction.	(Drewry et al., 2001; Drewry; Paton, 2005).
θ_{6kPa}: θ volumetric water content at Ψ_m -6 kPa as stated in Barbosa et al. (2020).						
Bulk Density	BD	$BD = \frac{Ms}{Vb}$	$0.9 \geq BD \leq 1.2$ Mg dm^{-3}	Ideal	For medium to fine-textured soils associated with field culture aiming at maximum production.	(Tormena et al., 2008).
			BD < 0.9 Mg dm^{-3}	Not Ideal	Yield loss due to reduced unsaturated water flow affects the availability of water and nutrients to plant roots.	(Reynolds et al., 2009; Reynolds et al., 2008).
			Between 1.25 and 1.30 Mg dm^{-3}	-	Crop yield loss due to inadequate soil aeration.	(Drewry et al., 2001).
Ms: kiln-dried soil mass in Mg; Vb: total soil volume in m^{-3}.						

S Index	SI	$S = -n(U_s - U_R)\left[1 + \frac{1}{m}\right]^{-(1+m)}$	S = 0.045	-	The division between soils of good structural quality and soils that tend to become degraded.	(Dexter, 2004; Andrade; Stone, 2009)
			S values ≤ 0.025	-	Thoroughly physically degraded soils.	(Andrade; Stone, 2009)

Us (g g^{-1}): Gravimetric water content at the saturation point (Ψ_m 0 kPa); UR (g g^{-1}): Gravimetric content of residual soil water, the same as U_{PWP}: permanent wilting point, (Ψ_m -1500 kPa); *m* is the fitted empirical parameter obtained by SWRC software.

For a better understanding of the response of the different preparations in this Cambisol with the use of various agricultural implements and regarding the practice of additional liming, were studied the limits of physical soil quality (LPSQ). These limits were established according to the literature described by Reynolds et al. (2009), previously approached in table 2.

2.6. Parameters of normalized pore volume distribution function

According to the methodology and equations proposed by Reynolds et al. (2009), the pore volume distribution function, $S_v(h)$ (dimensionless), was defined as the slope of the WRCs expressed in a graph with volumetric water content, θ ($m^3\ m^{-3}$) versus ln (h). The authors report plotting this function against the equivalent pore diameter (d_e, in μm). Thus, according to Warrick (2002), the pore diameter can be determined as a function of the capillary rise. In this way, the "normalized" pore volume distribution function, S*(h), is defined by dividing $S_v(h)$ by S_{vi}. S_{vi} represents the peak of the pore volume distribution, which corresponds to the slope of the WRC inflection point, highlighting that this occurs at the most frequent diameter value (D_{mode}).

The normalized pore volume distribution functions were also calculated according to Reynolds et al. (2009), using parameters of "location" D_{mean}, $D_{median,}$ and D_{mode} and "shape" standard deviation (SD), skewness (asymmetry) and kurtosis (peak), σ_G; *Sk* and *K*, respectively.

2.7. Plant measurement

At the time of soil sampling, stem diameter (SD) and plant height (PH) were measured, and the vegetative vigor was evaluated and calculated by the NDVI, according to Bhandari et al. (2012). The NDVI was assessed by a Green Seeker® sensor (the Green Seeker

TM optical sensor unit, model RT200) (Barbosa et al., 2020). The readings were carried out fortnightly, starting in October 2019 and ending in March 2021, made for all coffee plants in each preparation studied. The device was positioned 0.30 m before the coffee plant. Two readings were performed for each plant in each planting line plot (12 useful plants).

To enhance the comprehension of the NDVI of the coffee plant, the study of its phenological phases was adopted, following the methodology described in Camargo and Camargo (2001). This study was conducted during the evaluation period from October 2019 to March 2021. Altogether, four phenological phases were considered, designated as III: flowering, fruit forming and expansion – October to December 2019; IV: granation of fruits – January to March 2020; V: fruit ripening – April to June 2020; VI: rest, senescence of the branches - July to August 2020. III^2: flowering, fruit forming, and expansion – September to December 2020 and IV^2: granation of fruits – January to March 2021. An average of 360 readings were collected for each phase, with 72 readings of the vegetative index per preparation studied.

2.8. Data analyses

The data were treated as a split plot with two factors, soil preparer strategies (plot) and depths (split-plot). Furthermore, SP40 was treated as a reference preparer, and Natural was treated as a reference area to evaluate the effects of the other soil preparations, SP60, SP60AL, SP80, and SP80AL. Although, for the NDVI data, SP40 was also treated as a reference preparer, in this case, this data analysis was treated as a simple factorial, only associated with the soil preparation strategies responses. An analysis of variance was performed to compare the treatments studied. When significant, the Scott-Knott and Dunnett tests ($p < 0.05$) were applied to compare the mean values for soil physical quality indicators and NDVI data, respectively.

The WRCs modeling was generated from the packages *tidyverse* and *nlstools* (Baty et al., 2015). Specifically, for *nlstools*, the *nls* function was used, which developed the curves. The *nlstools* function was used to generate the confidence intervals using bootstrap, as described and evaluated in Vasques et al. (2019).

Linear correlations were also performed between the soil variables studied and plant measurements (SD, PH, and NDVI). These correlations were made from the *rcorr* function in the *Hmisc* package (Harrell Jr et al. 2019) by Pearson's correlation for each variable studied and its p-values to test the significance of the correlation. All data analyses were performed using the R 4.1.2 statistical program (R Core Team, 2021).

3. Results and discussion

3.1. Soil physical quality indicators

The effectiveness of deep tillage with the use of a soil homogenizer, subsoiler, and additional liming provided > P_{MAC}, < BD, > S, on average +44.19%, -10.42%, and +35.72%, respectively, concerning the other soil preparations and Natural condition to the first 0.40 m of the soil profile (Figure 3A, C and E). Increased water content at potentials from 0 to -2 kPa was also observed (Figures 2A and B and table 2 of supplementary material). These improvements can be associated with the structural relief of the dense layer diagnosed in the field by a typical structure in moderate blocks in the 0.05 to 0.20 m layer in the natural condition (Figure and table 1 of the supplementary material). Barbosa et al. (2020) previously reported that the soil homogenizer and subsoiler, regardless of the application of additional liming, favored aeration and drainage pores ($30 < Ø \leq 500$ μm), which had a direct association with > P_{MAC} and > P_{AWC} up to 0.20 m.

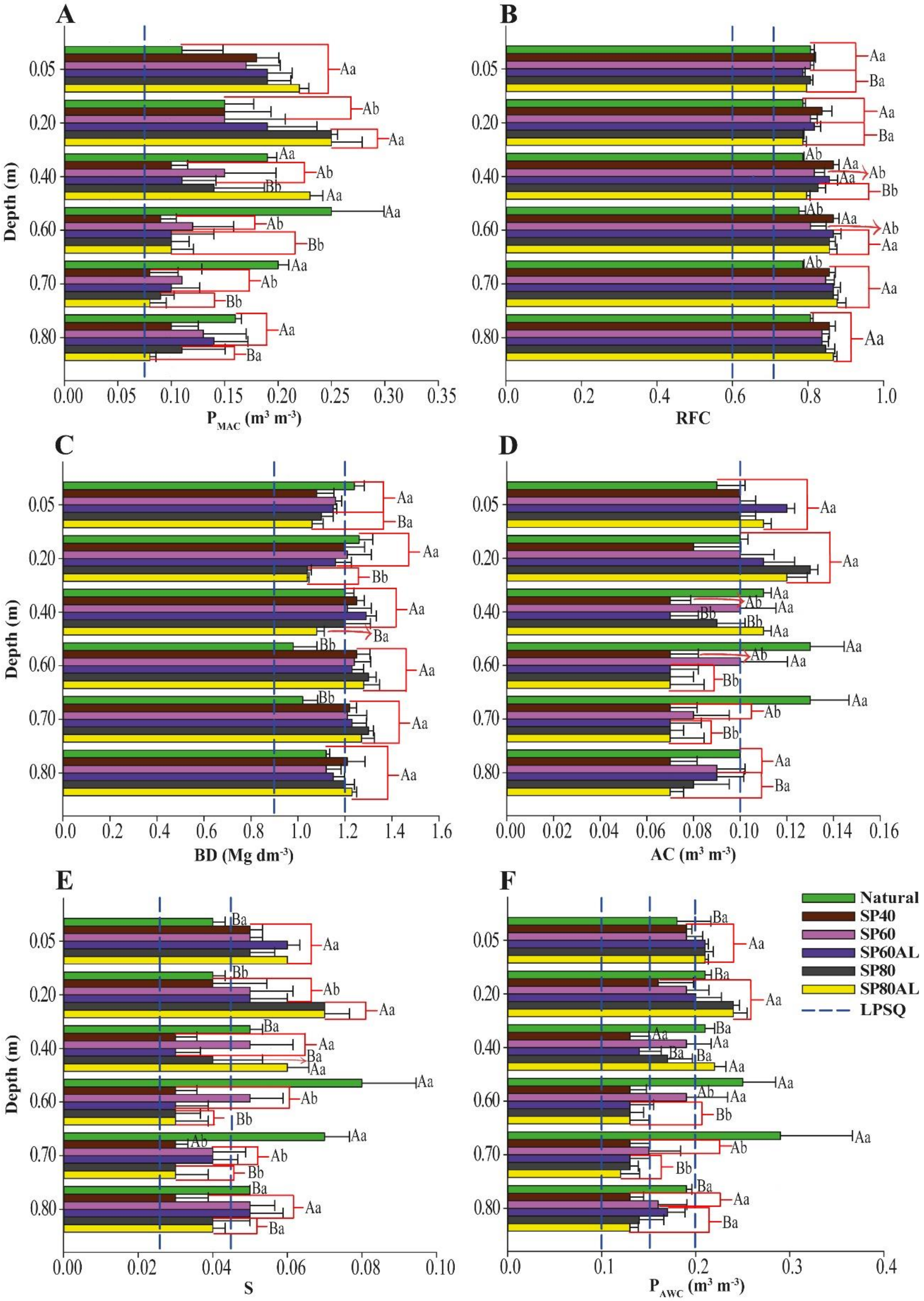


Figure 3. Soil physical quality indicators at different treatments: SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer;

SP80: planting furrow at 0.60 m and 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler; Natural: a native savannah vegetation area from Cerrado biome and depths (0-0.05; 0.15-0.20; 0.35-0.40; 0.55-0.60; 0.60-0.70 and 0.75-0.80). LPSQ: limits of physical soil quality defined in the world literature; P_{MAC} macroporosity; RFC relative field capacity; BD Bulk density; AC air capacity; S S Index; P_{AWC} available water capacity for plants. Means followed by the same lowercase letter do not differ for treatments within the same depth, and the same capital letter does not differ from each other for deep within the same treatment by the Scott-Knott test ($p < 0.05$).

The SP40 and SP60AL increased RFC concerning the Natural condition at 0.40 m, but at 0.60 m, SP60 was the only one that reduced RFC, which was equal to the Natural condition (Figure 3B). Barbosa et al. (2020) state that an increase in RFC under soil preparation indicates an increase in retention pores compared to the soil under natural conditions. However, this water can be strongly retained in tiny pores and, therefore, not readily available to plants. These results corroborate an increase in Cripto promoted by the SP40 and SP60AL at 0.40 m and the reduction of this same pore diameter by handling exclusively with the soil homogenizer at 0.40 and 0.60 m, as evidenced by figure 3 of the supplementary material. As for AC at 0.40 m, both SP60 and SP80AL are the only soil preparations that favored aeration capacity, on average +50%, especially when compared with the traditional furrowing rod (Figure 3D), indicating less possibility of aeration deficit, and therefore, not limiting the exploration of the soil profile by the roots (White, 2006; Reynolds et al., 2009).

The soil preparations from 0.60 m increased the BD (on average 18.17%) concerning the Natural condition (Figure 3C), which probably reflects the possibility of compaction in the action limits of the implements with rod work at 0.60 and 0.80 m, as observed by Silva et al.

(2021). The reflections of this increase in density were more expressive at depths of 0.60 and 0.70 m, where there is a reduction in P_{MAC}, AC, and P_{AWC}, except for SP60, which greatly reflected in the decrease of the S index of Dexter (2004) at these depths for the preparations applied concerning the Natural condition (Figures 3A, D, F and E). However, precisely at 0.60 m, between the soil preparer strategies, SP60 showed lower RFC, higher AC, and higher P_{AWC} (Figures 3B, D, and F) but did not promote an increase in the S index (Figure 3E). At a depth of 0.80 m, the SP80 and SP80AL were inefficient in promoting structural changes, matching the other preparations and Natural conditions for all indicators (Figure 3).

Bortolanza and Klein (2016) found results similar to those of the present study, where when applying liming in-depth, they observed a reduction in the physical quality caused by the higher density promoted due to the preparation of a Cambisol three years after the implementation of the experiment. However, better structural rate and increased base saturation at depth were observed by Santos et al. (2014) from the opening of the planting furrow to 0.60 m in Oxisol under coffee cultivation, followed by the addition of limestone, differing wildly from the results found here. Carducci et al. (2014) also observed better physical quality of an Oxisol with coffee plantation up to 0.35 m, favored by applying limestone up to 0.40 m and gypsum on the surface. However, this result does not exclude the physical effect caused by opening the planting furrow for the coffee plant since the last two researchers mentioned above-used equipment similar to the Big Mix of the present study, which allowed the deep opening of the furrow, homogenization, and chemical correction of the soil in up to 0.60 m.

Silva et al. (2016) observed structural changes in Cambisol, proposing management practices with the adoption of treatments with high doses of gypsum (28 Mg ha^{-1}). The use of this soil conditioner, when reaching depths along the profile due to its solubility, favored long-term structural reorganization (1.5 years) due to the increase of Ca^{2+}. Thus, this condition selected by the additional liming studied here, demonstrated the potential to improve the physical and hydric of this naturally shallow and dense Cambisol by mitigating problems associated with water deficit (Santos et al., 2014), which has excellent potential for optimization coffee plant development (Barbosa et al., 2020).

For the LPSQ, regardless of the assessed depth and the preparation adopted, the RFC values (Figure 3B) are above those established as the limit for ideal microbial production of nitrate of 0.7 (Drewry and Paton, 2005). Furthermore, although RFC values > 0.7 and P_{MAC} reduction indicate possible stress due to insufficient aeration, according to Reynolds et al. (2009), a $P_{MAC} > 0.07$ m^3 m^{-3}, as observed at 0.60 - 0.70 m (Figure 3A) indicates a good capacity of the soil to drain excess water facilitating root growth (Reynolds et al., 2009).

3.2. Deep tillage effects over time and soil reconsolidation

The extension of the soil preparation effect or the possible reconsolidation was observed considering the evaluations at the end of the 2nd cycle (obtained in 2017) from the data published by Barbosa et al. (2020) and at the end of the 5th cycle (data from the present study obtained in 2020) (Figure 4). The AC and the S index showed the most remarkable difference among the evaluated physical properties between the analyzed periods.

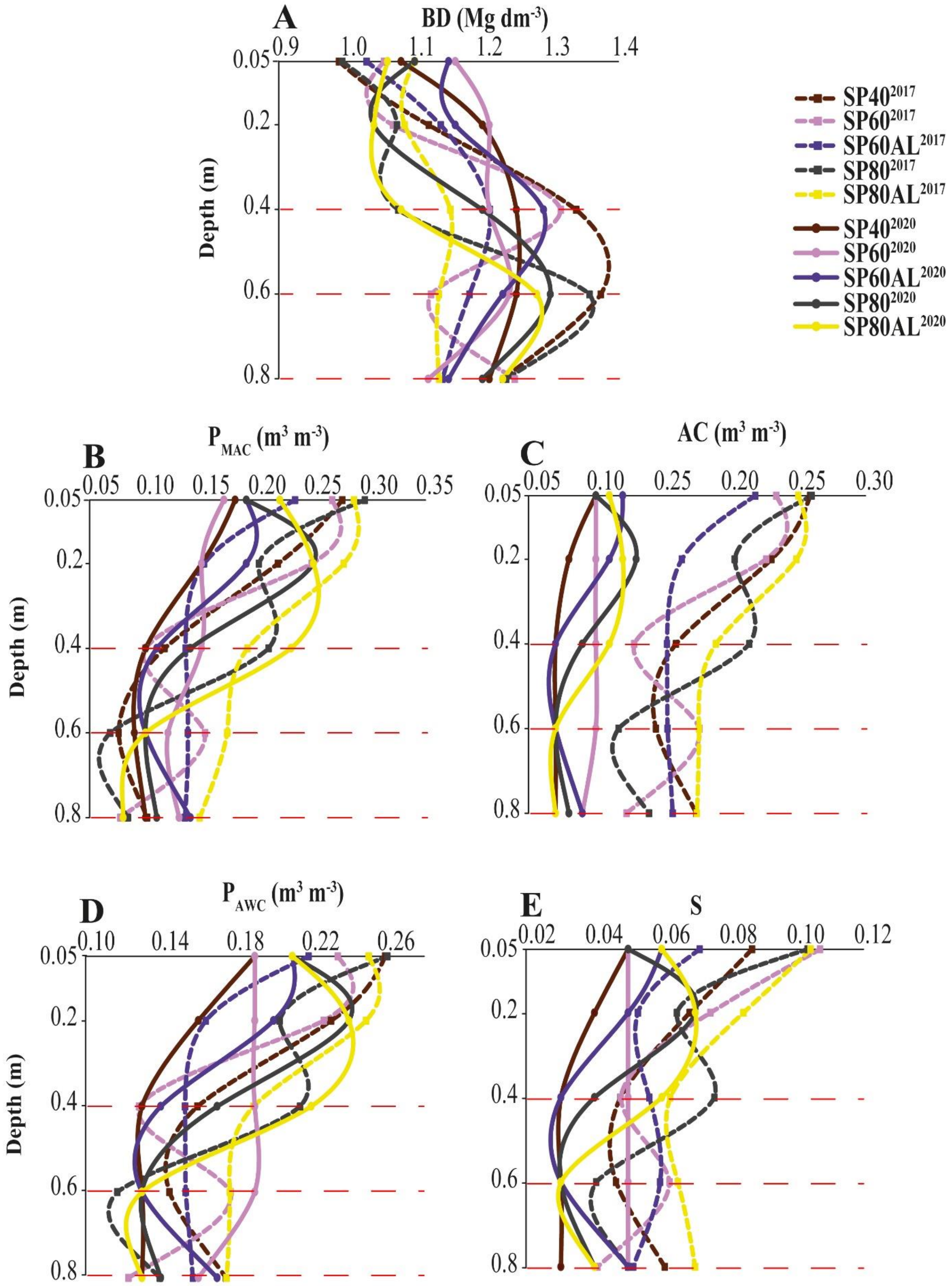


Figure 4. Evaluation of soil preparation strategies over time 2017 - 2020 to prove the long-term effects and the state of reconsolidation. BD Bulk density; P_{MAC} macroporosity; AC air capacity; P_{AWC} available plant water capacity; S S Index. $SP40^{2017}$; $SP60^{2017}$; $SP60AL^{2017}$;

SP80^{2017}; SP80AL^{2017}, data from (Barbosa et al., 2020). SP40^{2020}: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60^{2020}: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL^{2020}) using a soil homogenizer; SP80^{2020}: planting furrow at 0.60 m and 0.80 m with conventional fertilization and with additional liming (SP80AL^{2020}) using both soil homogenizer and subsoiler.

The AC was reduced (from the second to the 5th cycle) summarily for all preparations at all depths (Figure 4C), but with a marked deleterious effect on water availability (P_{AWC}) only for the SP40^{2020} in the entire profile, SP60^{2020} at 0.20 m and handling SP80AL^{2020} from 0.60 m (Figure 4D). Reichert et al. (2021) also observed a reduction in AC in naturally dense soil in which compaction occurred in its soil preparation and found the reconsolidation process in a short period due to the change in structure.

The physical quality of the soil indicated by the S index (Figure 4E) was also reduced in all preparations for any of the depths evaluated, which is yet another factor indicating that reconsolidation is a reality in soils submitted to tillage using machinery and agricultural implements (Reichert et al., 2017), as the effects from preparation may be short-lived (Busscher et al., 2002). According to Ghosh and Daigh (2020), subsoiling should be avoided in soils with predominant silt due to poor resistance and a tendency to reconsolidation. However, Cambisol, like the one in the present study, has pedological units in formation, with an incipient B horizon and with high silt (Bortolanza and Klein, 2016), as shown in table 1, but it has been adapted to the management conditions in coffee growing (Silva et al., 2016; Barbosa et al., 2020; Silva et al., 2021).

Drescher et al. (2011) and Nunes et al. (2014) observed temporary structural alterations promoted by mechanized operation with a scarifier equipped with a crushing roller in Oxisol (4.5 years) and Ultisol (1.5 years) due to soil reconsolidation and wetting and drying cycles. For our experimental site area, the reconsolidation process had already been indicated but not proven by Silva et al. (2021) after 1.5 years of implantation due to reduced hydraulic properties along the soil profile. However, the reconsolidation process was diagnosed through a reduction in hydraulic conductivity caused by wetting and drying cycles in a study by Moret and Arrúe (2007) under clayey loam soil.

SP40^{2020} and SP60^{2020}, up to 0.20 m, showed an increase in BD and its reduction between the time intervals at a depth of 0.40 m (Figure 4A). For SP80^{2020}, an increase in BD over time of 0.30 to 0.50 m is observed, which may indicate the reconsolidation of the system. It is observed that even for the SP40^{2020}, traditional soil preparation for the coffee crop (Barbosa et al., 2020), where there was no opening at 0.80 m, the BD decreased for this depth (Figure 4A), which possibly proves the inefficiency of the operation, mainly due to the subsoiler starting from the preparation in conditions of high humidity in the soil, leading to the structural damage such as increased density (Obour et al., 2018), which was confirmed by figure 3.

Reconsolidation can also be observed for the SP60AL^{2020}, which had a BD increase from 0.00 to 0.60 m, and from 0.60 - 0.80 m for the SP80AL^{2020} (Figure 4A), together with the reduction of its macroporosity in this same layer (Figure 4B). It is important to note that the SP80AL^{2020} action was the longest for the 0.00 - 0.40 m layer, with the structural relief lasting between the sampled years. According to studies by Ahuja and Green (2022), reconsolidation occurs naturally. However, it can significantly affect the volume of macropores due to increased density and modification of the structure over the years after handling.

Bortolanza and Klein (2016), also studying deep liming, did not observe pronounced effects of this practice, as they found a reduction in the physical quality of the soil due to compaction caused by the introduction of machines outside the friability zone. Which, together with the wetting and drying cycles, lead to a condition of reconsolidation (Ahuja and Green, 2022). For this reason, Blumenschein et al. (2019) state that the best effects of subsoil liming are obtained one year after application, justifying the results of (Barbosa et al., 2020). This condition corroborates with Holland et al. (2018) that the physical quality of the soil is at least maintained or improved by liming. However, the detection of this change will vary significantly over time.

3.3. Plant growth response

The NDVI results were associated with the climatic conditions of the region where the experiment was implemented for 2019 to 2021 (Figure 5), corresponding to the fifth harvest of the crop. A drier period, characteristic of the study region, occurs between April and September when rainfall levels reach below 45 mm (Figure 5). There are at least six months of water deficit in the soil that is reflected in the response of the coffee plant, significantly altering its vegetative vigor, measured by the NDVI. Maciel et al. (2020) confirm the existing correlation between the water condition of the coffee plant and NDVI. These authors, studying an area close to the present study region, also found precipitation lower than expected, with a water deficit. This scenario led to changes in the photosynthetic rate and chlorophyll due to high dehydration from the plant's water stress, causing a lower NDVI.

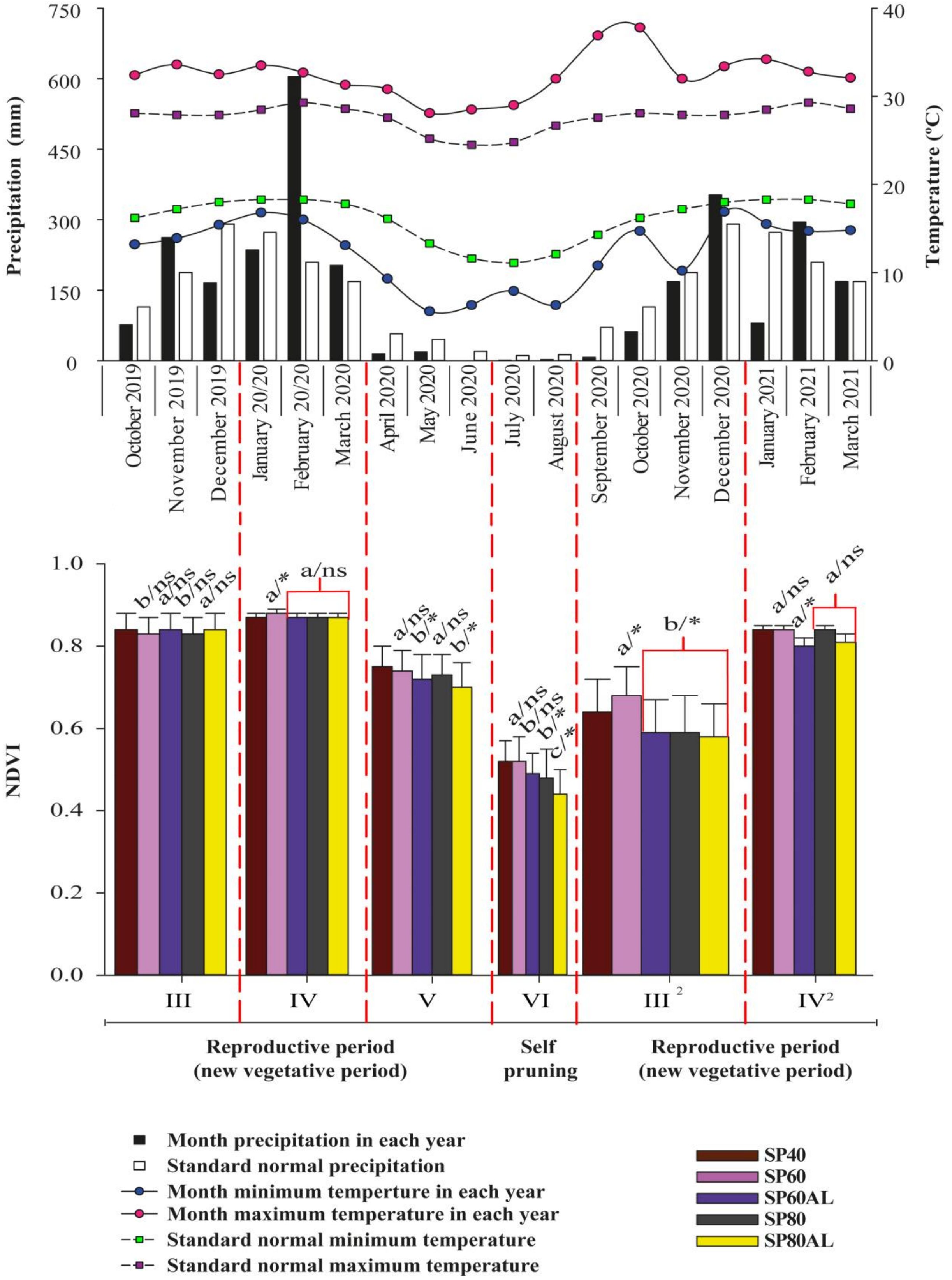


Figure 5. 2019 to 2021 data from São João del Rei weather station (21.25° S, 44.24° W) and standard climatological normals from the period 1981-2010. Source: INMET, 2022. NDVI - normalized difference vegetation index evaluated from 2019 to 2020 for the different

preparations. SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler. Bars followed by the same lowercase letters do not differ by the Skott-Knott test ($p < 0.05$) and compare the preparations (SP60; SP60AL; SP80, and SP80AL) with each other. Bars followed by an * differ from each other by Dunnett's test ($p < 0.05$), ns: not significant by the F test ($p < 0.05$) when compared to the reference preparation (SP40).

It was possible to observe a relationship between the phenological phases and NDVI. Hwang et al. (2020), studying intensive management of coffee plants in Ethiopia, point out that the fluctuations that occur in the NDVI are directly related to phenological changes, which in turn are related to the variation in precipitation, as they affect the leaf area, reflecting on the vegetative index of the crop. Figure 5 shows a lower NDVI in stages V and VI. In these vegetative phases, fruit maturation, senescence, and death of productive branches already occur, coinciding with the dry season's beginning. III^2, on the other hand, is associated with flowering and fruit expansion (Camargo and Camargo, 2001), and this phase is related to the end of the dry season, where the NDVI values start to increase again.

Volpato et al. (2013), studying coffee plants in a region close to the present study, observed a 50% drop in NDVI values, justified by water deficit, smaller leaf area, and leaf fall, and because it coincides with the grain harvest period. These results are corroborated by Junges et al. (2017), studying the grapevine culture, pointing out that the NDVI oscillation is associated with the phenological phases. These authors indicate that the highest NDVI was obtained during the fruiting and vegetative period due to leaf expansion and canopy closure.

Taugourdeau et al. (2014) observed changes in the NDVI obtained by the MODIS sensor (remotely) due to adopting different fertilizer management for phases associated with the pruning and renewal of coffee plantations in Costa Rica. Brunsell et al. (2009) demonstrated the relationship between NDVI and coffee yield but needed to investigate the good associations with the phenological stages of the crop. However, the impacts of soil attributes in association with the NDVI of coffee plants needed to be considered in previous studies. However, Barbosa et al. (2020) associated NDVI with soil physical quality indices. On the other hand, Santos et al. (2014) state that soil moisture in the root zone was highly correlated with the normalized difference vegetation index in coffee areas.

Compared to the traditional soil preparation, the strategies with additional liming presented NDVI alteration during the phenological phases V, VI, and III^2 (Figure 5). Thus, SP60AL and SP80AL reduced the vigor of coffee plants by approximately 5.75% and 10%, respectively, which was not expected considering the chemical correction in depth by additional liming since this same soil preparation significantly affected the NDVI of this same coffee plants at the end of the 2nd cycle (Barbosa et al., 2020).

After five years of planting, the present study did not observe a significant impact on the NDVI from additional liming. This lack of effect could be attributed to the insufficient liming applied during the initial soil preparation, which did not persist long enough to substantially impact the vegetation by the end of the 5th coffee cycle. In a meta-analysis conducted by Li et al. (2019) that analyzed various studies published worldwide since 1980, it was determined that the optimal duration for liming is three years. This duration effect is closely tied to the changing environmental conditions over time.

The SP80AL tillage showed the lowest NDVI concerning the other soil tillages in phenological phases V and VI in the driest period of the year. Considering the potential improvements in physical and water quality offered by this preparation strategy already presented in previous sections up to 0.40 m (Figure 3 and Figures 2, 3, 4, and 5 of the supplementary material), these results (Figure 5) were not expected. However, intensive management practices in coffee areas reduce leaf area and photosynthesis, affecting the optical properties and their interaction associated with spectral reflectance, thus reducing the vegetation index by normalized difference (Hwang et al., 2020). We suggest that this condition, as noted for coffee plants with fifteen months years of cultivation, mainly implanted under the Cerrado region, can occur when the plants have a more significant translocation of photoassimilates to the expanding root system due to good soil physical quality for this (Silva et al., 2019). The aerial part may show a reduction in growth, which, together with the water deficit conditions, reflects on its vegetative vigor.

A correlation analysis was performed to establish the influence of the physical quality indicators on the indicative parameters of plant growth and vigor (Figure 6). In general, without distinction between the soil preparation strategies (Figure 6A), it is observed that the plant parameters are more sensitive to changes in some physical quality indices up to 0.40 m depth. The increase in plant height with an increase in P_{AWC} (+0.76***) in the surface layer and with an increase in P_{MAC} (+0.61*) and consequent reduction in BD (-0.59*) at 0.20 m stand out, as well as reported by Barbosa et al. (2020). NDVI correlated better with FMacro (+0.70), Mesopores (+0.55*), and RFC (+0.52*) and negatively with S-index (-0.54*) and AC (+0.52*) at 0.05 m depth. At 0.20 m depth, NDVI increased with decreasing P_{MAC} (-0.53*) and D_{mode} (-0.59*). Thus, the increase in aeration capacity and water availability was relevant for plant growth in height in the 0.00 - 0.20 m layer, even with lower NDVI.

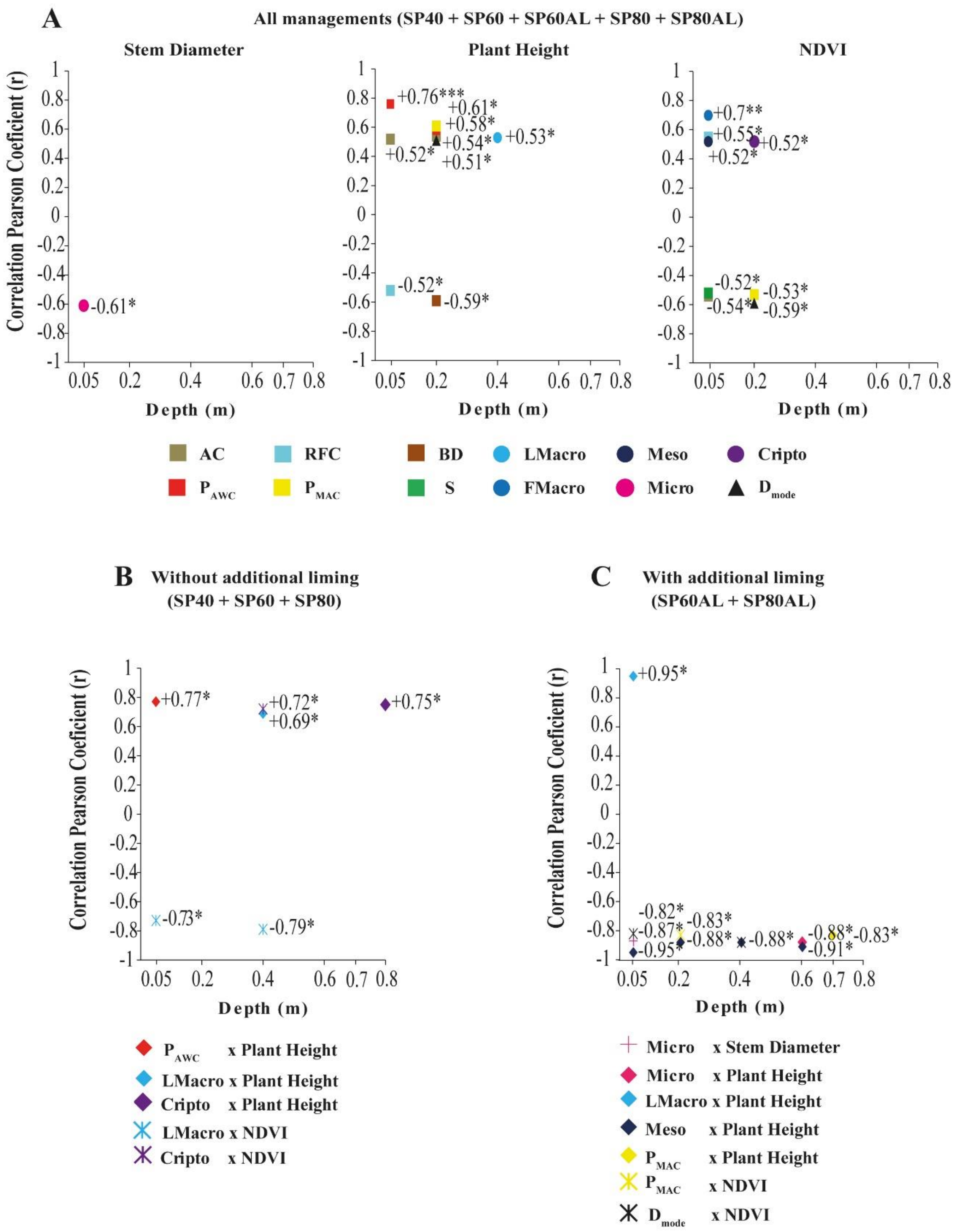


Figure 6. Pearson correlation between plant parameters, stem diameter, plant height, and NDVI with soil physical quality indicators and S*(h) location parameters for the studied soil profile (A) and considering the treatments groupings SP40, SP60, and SP80: without additional liming (B), and SP60AL and SP80AL: with additional liming (C). (*) significant value at 5% probability; (**) significant value at 1% probability and (***) significant value at

0.1%. Only significant correlations were shown. P_{MAC} macroporosity; RFC relative field capacity; BD Bulk density; AC air capacity; S S Index; P_{AWC} available water capacity for plants; LMacro: large macropores (> 147 μm); FMacro: fine macropores (147-73 μm); Meso: LMeso: large mesopores (73-49 and 49-29 μm) + AMeso: average mesopores (29-9 and 9-2.9 μm) + FMeso: fine mesopores (2.9-0.6μm); Micro: micropores (0.6-0.2 μm); Cripto: criptopores (> 0.2 μm); D_{mean}, D_{median} and D_{mode} refer to the mean, median and modal values respectively of d_e (equivalent pore diameter). SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler.

Figures 6B and 6C show separately the preparations that did not receive and received the practice of additional liming, which made it possible to observe that the plant parameters were influenced by the alteration of some SPQI up to 0.80 m in depth. For soil preparation without additional liming (Figure 6B), plant height was favored by P_{AWC} on the surface, by LMacro at 0.40, and by Cripto at 0.80 m. Higher NDVI values occurred with LMacro reduction at 0.05 and 0.40 m and Cripto increase at 0.80 m. Thus, deep tillage favored pores with larger diameters, mainly in the superficial layer, which, together with an improvement in the availability of water for the plants (Cockroft and Olsson, 1997; Reynolds et al., 2009), favored the growth and vigor of the coffee plant. NDVI and plant height were also favored by higher Cripto, i.e., the presence of tiny pores.

For soil preparation strategy with additional liming (Figure 6C), it is observed that pore changes imposed by chemical amendments and deep tillage led to a greater number and significant correlations with plant growth parameters. There is an increase in stem diameter due to the reduction of Micro in surface area (-0.87*). As well as larger plants, as LMacro increases at this depth, it reduces Micro and, at the same time, P_{MAC} at greater depths. According to Carducci et al. (2015a), knowledge of the spatial geometry of pores contributes to understanding the dynamics of water processes associated with agricultural practices implemented in the soil, which was also confirmed by Barbosa et al. (2020) and Silva et al. (2021).

The high correlation of plant height with an increase in LMacro (+0.95*) on the surface (0.05 m) and a reduction in Meso (-0.91*) and Micro (-0.88*) up to 0.60 m depth indicate that the effect of structural relief in this 5th cycle was beneficial for coffee plant growth. Furthermore, the exclusive influence of the SP80AL resulted in improved D_{mean}, D_{median}, and D_{mode} (Figure 4A of the supplementary material) and consistent behavior of SD, skewness, and kurtosis (Figure 4B of the supplementary material) by favoring LMacro and FMacro, pores with $Ø > 100$ µm, (Figures 3A and D of the supplementary material). This result was further supported by the normative distribution of pores (Figures 5A, B, and C of the supplementary material), which showed a rightward shift compared to the Natural condition, indicating an increase in larger diameter pores (Reynolds et al., 2009) up to 0.40 m.

On the other hand, NDVI, unlike plant height, showed a high negative correlation with P_{MAC} and D_{mode} up to 0.40 m. This fact is associated with the Leptocurtic kurtosis pattern of the pore distribution (Figure 4B of the supplementary material), which indicates the probability of obtaining values that do not approach the mean, but the median or mode (Reynolds et al., 2009). This condition justifies a reduction in the ability to provide water to the plants, as $> D_{mode}$ contributed to the decrease of Meso. However, as the plants are established at the end of the 5th cycle, the smallest Meso impacts less than a P_{MAC} reduction, as the root system has deepened and can absorb water in depth (Silva et al., 2015).

4. Conclusions

The hypothesis tested in this study that the effects of deep preparation would last for five years after planting, was confirmed for naturally dense soils. Five years after planting, improvements in the soil's physical quality and the plants' measurements are proven to be up to 0.40 m deep. This condition occurs when strategies include soil homogenizer at 0.60 m, subsoiling at 0.80 m, and additional liming compared to the traditional method that uses only a furrowing rod at 0.40 m. A reduction in soil density and consequent improvement in aeration indicators (AC and P_{MAC}) and S index were observed, which indicates a favorable condition for root growth in depth and access to available water for plants. The plants responded positively to deep preparation combined with the chemical amendments, confirmed by the significant correlations for P_{MAC}, Meso, and D_{mode} in up to 0.70 m of depth, reflected in the increase in stem diameter, growth in height, and NDVI of the plants, contributing in mitigating the effects of edaphic drought. The different agricultural implements used to prepare this Cambisol still showed the results of the compaction caused at the bottom of the planting furrow, reducing the physical structure quality by 0.60 to 0.70 m due to soil preparation outside the friability zone. For a depth of 0.80 m, the inefficiency of operation and disappearance of the effects of the subsoiler were verified, justified by the natural reconsolidation of the soil, mainly under preparation strategy with additional limestone. Therefore, it is crucial for coffee growers to carefully plan preparation strategies that prioritize thorough preparation, particularly in naturally dense Cambisol, to prevent the loss of structural quality.

5. References

Ahuja, L.R., Green, T.R., 2022. Modeling Processes and Their Interactions in Cropping Systems: Challenges for the 21st Century in Ahuja, R.L., Kersebaum, K.C., Wendroth, O. (Eds.), Advances in Agricultural Systems Modeling. © 2022 American Society of Agronomy, Inc. / Crop Science Society of America, Inc. / Soil Science Society of America, Inc, pp.333–358.

Andrade, R.S., Stone, L.F., 2009. S index as an indicator of physical quality of Brazilian 'Cerrado' soils. Rev. Bras. Eng. Agríc. Ambient. 13, 382–388. https://doi.org/10.1590/S1415-43662009000400003.

Andrade, R., Stone, L., 2011. Estimation of moisture at field capacity in soils under 'Cerrado. Rev. Bras. Eng. Agríc. Ambient. 15, 111–116. https://doi.org/10.1590/S1415-43662011000200001.

Ayele, A., Worku, M., Bekele, Y., 2021. Trend, instability and decomposition analysis of coffee production in Ethiopia (1993–2019). Heliyon. 7, 1–7. https://doi.org/10.1016/j.heliyon.2021.e08022.

Azevedo, R.P., Corinto, L.M., Peixoto, D.S., De Figueiredo, T., Silveira, G.C., Peche, P.M., Pio, L.A., Pagliari, P.H., Curi, N., Silva, B.M., 2022. Deep Tillage Strategies in Perennial Crop Installation: Structural Changes in Contrasting Soil Classes. Plants,. 11, 17, 2255. https://doi.org/10.3390/plants11172255

Barbosa, S.M., Oliveira, G.C.de., Silva, B.M., Benevenute, P.A.N., Silva, R.F.DA., Curi, N., Moretti, B.DA.S., Silva, S.H.G., Norton, L.D., Pereira, V.M., 2020. Deep furrow and additional liming for coffee cultivation under first year in a naturaly dense Inceptisol. Geoderma. 357, 113934. https://doi.org/10.1016/j.geoderma.2019.113934.

Bhandari, A., Kumar, A., Singh, G., 2012. Feature Extraction using Normalized Difference Vegetation Index (NDVI): A Case Study of Jabalpur City. Proc. Technol. 6, 612–621. https://doi.org/10.1016/j.protcy.2012.10.074.

Baty, F., Ritz, C., Charles. S., Brutsche, M., Flandrois, J.P., Delignette-Muller, M.L., 2015. A Toolbox for Nonlinear Regression in R: The Package nlstools. J. Stat. Softw. 66, 1–21. https://doi.org/10.18637/jss.v066.i05.

Blumenschein, T.G., Nelson, K.A., Motavalli, P.P., 2019. Changes in subsoil acidity with a new deep vertical lime placement practice for conservation tillage systems J. Soil Water Conserv. 74, 426–438. https://doi.org/10.2489/jswc.74.5.426.

Bortolanza, D.R., Klein, V.A., 2016. Soil chemical and physical properties on an Inceptisol after liming (surface and incorporated) associated with gypsum application. Rev. Bras. Ciênc. Solo. 40, 1–13. https://doi.org/10.1590/18069657rbcs20150377.

Bouma, J., 1973. Guide to the Study of Water Movement in Soil Pedons Above the Watertable . Wisconsin Geological and Natural History Survey.

Brunsell, N.A., Pontes, P.P.B., Lamparelli, R.A.C., 2009. Remotely sensed phenology of coffee and its relationship to yield. GIsci. Remote Sens. 46, 289–304. https://doi.org/10.2747/1548-1603.46.3.289.

Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., Tursina, T., 1985. Handbook for soil thin section description. Waine Research.

Busscher, W.J., Bauer, P.J., Frederick, J.R., 2002. Recompaction of a coastal loamy sand after deep tillage as a function of subsequent cumulative rainfall. Soil Tillage Res. 68, 49–57. https://doi.org/10.1016/S0167-1987(02)00083-1.

Camargo, Â.P.D., Camargo, M.B.P.D., 2001. Definition and outline for the phenological phases of arabic coffee under Brazilian tropical conditions. Bragantia. 60, 65–68. https://doi.org/10.1590/S0006-87052001000100008.

Carducci, C.E., Oliveira, G.C., Curi, N., Heck, R.J., Rossoni, D.F.F., Carvalho, T.S.S.; Costa, L.L., 2015a. Gypsum effects on the spatial distribution of coffee roots and the pores system in oxidic Brazilian Latosol. Soil Tillage Res. 145, 171–180. https://doi.org/10.1016/j.still.2014.09.015.

Carducci, C.E., Oliveira, G.C., Lima, J.M., Rossoni, D.F., Costa, A.L., Oliveira, L.M., 2014. Distribuição espacial das raízes de cafeeiro e dos poros de dois Latossolos sob manejo conservacionista. Rev. Bras. Eng. Agríc. Ambient. 18, 270–278. https://doi.org/10.1590/S1415-43662014000300005.

Carducci, C.E., Oliveira, G.C., Oliveira, L., Barbosa, S.M., Silva, E.A., 2015b. Retenção de água do solo sob sistema conservacionista de manejo com diferentes doses de gesso. Rev. Cienc. Agrar. 58, 284–291. http://dx.doi.org/10.4322/rca.2014.

Cockroft, B., Olsson, K.A., 1997. Case study of soil quality in southeastern Australia: management of structure for roots in duplex soils. In Developments in Soil Science. 25, 339–350. https://doi.org/10.1016/S0166-2481(97)80043-8.

Conab, Companhia Nacional de Abastecimento. Acompanhamento da safra brasileira, café, safra 2023, 2º levantamento, Maio de 2023. 10, 1–45. https://www.conab.gov.br/info-agro/safras/cafe (accessed 10 June 2023).

Companhia Nacional de Abastecimento (Conab), 2022. Acompanhamento da safra brasileira, café, safra 2022 1º levantamento, janeiro de 2022, volume 9, número 1.

Dexter, A.R., 2004. Soil physical quality: part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120, 201–214. https://doi.org/10.1016/j.geoderma.2003.09.004.

Dexter, A.R., Bird, NRA, 2001. Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. Soil Till. Res. 57, 203–212. https://doi.org/10.1016/S0167-1987(00)00154-9.

Dexter, A.R., Czyż, E.A., Richard, G., Reszkowska, A., 2008. A user-friendly water retention function that takes account of the textural and structural pore spaces in soil. Geoderma 143, 243–253. https://doi.org/10.1016/j.geoderma.2007.11.010.

Doran, J.W., Mielke, L.N., Power, J.F., 1990. Microbial activity as regulated by soil waterfilled pore space. Symposium III-3, Ecology of Soil Microorganisms in the Microhabitat Environments III. Transactions of the 14th International Congress of Soil Science, August 12–18, Kyoto, Japan, pp. 94–99.

Dourado Neto, D., Nielsen, D.R., Hopmans, J.W., Reichardt, K., Bacchi, 2000. Software to model soil water retention curves (SWRC, version 2.00). Sci. agric. 57, 191–192. https://doi.org/10.1590/S0103-90162000000100031.

Drescher, M.S., Eltz, F.LF., Denardin, J.E., Faganello, A., 2011. Persistência do efeito de intervenções mecânicas para a descompactação de solos sob plantio direto. Rev. Bras. Ciênc. Solo. 35, 1713–1722. https://doi.org/10.1590/S0100-06832011000500026.

Drewry, J.J., Cameron, K.C., Buchan, G.D., 2001. Effect of simulated dairy cow treading on soil physical properties and ryegrass pasture yield. New Zealand J. Agric. Res. 44, 181–190. https://doi.org/10.1080/00288233.2001.9513476.

Drewry, J.J., Paton, R.J., 2005. Soil physical quality under cattle grazing of a winter-fed brassica crop. Aust. J. Soil Res. 43, 525–531. https://doi.org/10.1071/SR04122.

FAO, 2001. Food and Agriculture Organization of the United Nations. Inceptisols. Set #5 in Lecture notes on the major soils of the world, Driessen, P., Deckers, J., Spaargaren, O., Nachtergaele, F. (eds.). World Soil Resources Reports 94. FAO, Rome.

Ferreira, M.M., Marcos, Z.Z., 1983. Estimativa da capacidade de campo de Latossolo Roxo distrófico e regossolo através do ponto de inflexão da curva característica de umidade. Ciência e Prática. 7, 96–101. https://doi.org/10.11606/D.11.1980.tde-20210919-102521.

Ghosh, U., Daigh, A.L.M., 2020. Soil compaction problems and subsoiling effects on potato crops: A review. Crop, Forage & Turfgrass Management. 6, 1–10. https://doi.org/10.1002/cft2.20030.

Guimarães, P.T.G., Garcia, A.W.R., Alvarez V.V.H., Prezotti, L.C., Viana, A.S., Miguel, A.E., Oliveira, J.D., 1999. Cafeeiro. CFSMG - Comissão de Fertilidade do Solo do Estado de Minas Gerais. Recomendação para o uso de corretivos e fertilizantes em Minas Gerais, 5ª aproximação. Viçosa.

Harrell, F. E.Jr., Dupont, C., 2019. Hmisc: Harrell miscellaneous (R package version 4.2-0)[Computer software]. https://CRAN.R-project.org/package=Hmisc.

Holland, J.E., Bennett, A.E., Newton, A.C., White, P.J., McKenzie, B.M., George, T.S., Pakeman, R.J., Bailey, J.S., Fornara, D.A. Hayes, R.C., 2018. Liming impacts on soils, crops and biodiversity in the UK: A review. Sci. Total Environ.. 610–611, 316–332. https://doi.org/10.1016/j.scitotenv.2017.08.020.

Horta, I.M.F., Pereira, J.A.A, Marques, J.J., Carvalho, L.M.T., 2009. Levantamento de reconhecimento com apoio digital dos solos do município de Nazareno-MG. Ciênc. agrotec. 33, 1940–1947. https://doi.org/10.1590/S1413-70542009000700042.

Hwang, B., Hundera, K., Mekuria, B., Wood, A., Asfaw, A., 2020. Intensified Management of Coffee Forest in Southwest Ethiopia Detected by Landsat Imagery. Forest. 11, 1–21. https://doi.org/10.3390/f11040422.

Junges, A.H., Fontana, D.C., Anzanello, R., Bremm, C., 2017. Índice de vegetação por diferença normalizada obtido por sensor remoto de superfície para caracterização do ciclo de videiras no Rio Grande do Sul, Brasil. Ciênc. Agrotec. 41, 543–553. https://doi.org/10.1590/1413-70542017415049016.

Klein, V.A., 1998. Propriedades físico-hídrico-mecânicas de um Latossolo Roxo, sob diferentes sistemas de uso e manejo, 150p. Tese (Doctoral dissertation) Escola Superior de Agricultura de Luiz de Queiroz, Piracicaba, Universidade de São Paulo.

Klute, A., 1986. Water retention: Laboratory methods. In: Klute, A. (Ed.), Methods of Soil Analysis: Physical and Mineralogical Methods, 2.ed. American Society of Agronomy, Madison, pp. 635–660.

Köppen, W. Das geographisca System der Klimate. Gebr, Borntraeger, 1936. p.1–44.

Li, Y., Cui, S., Chang, S. X., Zhang, Q., 2019. Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: a global meta-analysis. Journal of Soils and Sediments. 19, 1393-1406. https://doi.org/10.1007/s11368-018-2120-2

Maciel, D.A., Silva, V.A., Alves, H.M.R., Volpato, M.M.L., Barbosa, J.P.R.A., Souza, V.C.O., Santos, M.O., Silveira, H.R.O., Dantas, M.F., Freitas, A.F., Carvalho, G.R., Santos, J.O., 2020. Leaf water potential of coffee estimated by landsat-8 images. PloS one. 15, 1–13. https://doi.org/10.1371/journal.pone.0230013.

Mafes, 2017. Big mix AS-2, preparador de solo. 3p. http://mafes.com.br/big_mix.html, (accessed 05 May 2018).

Moret, D., Arrúe, J.L., 2007. Dynamics of soil hydraulic properties during fallow as affected by tillage. Soil Tillage Res. 96, 103–113. https://doi.org/10.1016/j.still.2007.04.003.

Mualem, Y.A., 1976. New model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research. 12, 513–522. https://doi.org/10.1029/WR012i003p00513.

Nunes, M.R., Pauletto, E.A., Denardin, J.E., Faganello, A., Pinto, L.F.S., Scheunemann, T., 2014. Persistência dos efeitos da escarificação sobre a compactação de Nitossolo sob plantio direto em região subtropical úmida. Pesq. Agropec. Bras. 49, 531–539. https://doi.org/10.1590/S0100-204X2014000700005.

Obour, P.B., Kolberg, D., Lamande, M., Borresen, T., Edwards, G., Sorensen, C.G., Munkholm, L.J., 2018. Compaction and sowing date change soil physical properties and crop yield in a loamy temperate soil. Soil Tillage Res. 184:153–163. https://doi.org/10.1016/j.still.2018.07.014.

Oliveira, G.C.; Silva, B.M.; Carducci, C.E.; Silva, S.H.G.; Serafim, M.E.; Barbosa, S.M.; Silva, E.A.; Melo, L.B.B.; Benevenute, P.A.N., 2019. Melhoria físico-hídrica do ambiente radicular do cafeeiro em condições de sequeiro e implicações no uso da água. In Tópicos em Ciência do Solo; Severiano, E.C., Moraes, M.F., Paula, A.M., Eds.; Sociedade Brasileira de Ciência do Solo (SBCS). Viçosa. pp. 70–140.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Reichert, J.M., Brandt, A.A., Rodrigues, M.F., Veiga, M., Reinert, D.J., 2017. Is chiseling or inverting tillage required to improve mechanical and hydraulic properties of sandy clay loam soil under long-term no-tillage? Geoderma. 301, 72–79. https://doi.org/10.1016/j.geoderma.2017.04.012.

Reichert, J.M., Fontanela, E., Awe, G.O., Fasinmirin, J.T., 2021. Is cassava yield affected by inverting tillage, chiseling or additional compaction of no-till sandy-loam soil? Revista Rev. Bras. Cienc. Solo. 45, 1–25. https://doi.org/10.36783/18069657rbcs20200134.

Reynolds, W., Drury, C.F., Yang, X., Tan, C., 2008. Optimal soil physical quality inferred through structural regression and parameter interactions. Geoderma. 146, 466–474. https://doi.org/10.1016/j.geoderma.2008.06.017.

Reynolds, W.D., Drury, C.F., Tan, C.S., Fox, C., Yang, X.M., 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma. 152, 252–263. https://doi.org/10.1016/j.geoderma.2009.06.009.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Araújo Filho, J.C., Oliveira, J.B., Cunha, T.J.F., 2018. Sistema brasileiro de classificação de solos. Fifth ed. Brasília.

Santos, W.J.R., Silva, B.M., Oliveira, G.C., Volpato, M.M.L., Lima, J.M., Curi, N., Marques, J.J., 2014. Soil moisture in the root zone and its relation to plant vigor assessed by remote sensing at management scale. Geoderma, 221–222, 91–95. https://doi.org/10.1016/j.geoderma.2014.01.006.

Silva, B.M., Oliveira, G.C., Serafim, M.E., Silva, E.A., Guimaraes, P.T.G., Melo, L.B.B., Norton, L.D., Curi, N., 2019. Soil moisture associated with least limiting water range, leaf water potential, initial growth and yield of coffee as affected by soil management system. Soil Tillage Res. 189, 36–43. https://doi.org/10.1016/j.still.2018.12.016.

Silva, B.M., Santos, W.J.R., Oliveira, G.C., Lima, J.M., Curi, N., Marques, J. J.G.S.M., 2015. Soil moisture space-time analysis to support improved crop management. Ciênc. agrotec. 39, 39–47. https://doi.org/10.1590/S1413-70542015000100005.

Silva, É.A., de Oliveira, G.C., Carducci, C.E., Silva, B.M., Serafim, M.E., 2016. Aggregates morphometry of a Inceptisol under conservationist system. Semin. Agrar. 37, 1165–1176. https://doi.org/10.5433/1679-0359.2016v37n3p1165.

Silva, R.F., Severiano, E.C., Oliveira, G.C., Barbosa, S.M., Peixoto, D.S., Tassinari, D., Silva, B.M., Silva, S.H.G., Dias Júnior, M.S., Figueiredo, T.A.F.R., 2021. Changes in soil profile hydraulic properties and porosity as affected by deep tillage soil preparation and Brachiaria grass intercropping in a recent coffee plantation on a naturally dense Inceptisol. Soil Tillage Res. 213, 105127. https://doi.org/10.1016/j.still.2021.105127.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed.; USDA-NRCS: Washington, DC, USA.

Taugourdeau, S., Le Maire, G., Avelino, J., Jones, J.R., Ramirez, L.G., Quesada, M.J., Charbonnier, F., Gómez-Delgado, F., Harmand, J., Rapidel, B., Vaast, P., Roupsard, O., 2014. Leaf Area Index as an Indicator of Ecosystem Services and Management Practices: An Application for Coffee Agroforestry. Agric. Ecosyst. Environ. 192, 19–137. https://doi.org/10.1016/j.agee.2014.03.042.

Torga, G.N., Spers, E.E., Perspectives of global coffee demand. Coffee Consumption and Industry Strategies in Brazil, p.21-49, 2020.

Tormena, C.A., da Silva, A.P., Imhoff, S.D.C., Dexter, A.R., 2008. Quantification of the soil physical quality of a tropical oxisol using the S index. Sci. Agric. 65, 56–60. https://doi.org/10.1590/S0103-90162008000100008.

United Nations. Progress towards the Sustainable Development Goals: Report of the Secretary-General (Advance, unedited copy)] [Publication: Progress towards the Sustainable Development Goals: Report of the Secretary-General (E/2021/58) (30 April 2021)]. Available:

https://sustainabledevelopment.un.org/content/documents/27610SG_SDG_Progress_report_2021.pdf (accessed 10 January 2023).

van GENUCHTEN, M.T.A., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x.

Vasques, I. C., Souza, A.A., Morais, E.G., Benevenute, P.A., da Silva, L.D.C., Homem, B.G., Casagrande, D.R., Silva, B.M., 2019. Improved management increases carrying capacity of Brazilian pastures. Agric. Ecosyst. Environ. 282, 30–39. https://doi.org/10.1016/j.agee.2019.05.017.

Volpato, M.M.L., Vieira, T.G.C., Alves, H.M.R., Santos, W.J.R.D., 2013. Imagens do sensor Modis para monitoramento agrometeorológico de áreas cafeeiras. Coffee Science. 8, 176–182. http://www.sbicafe.ufv.br:80/handle/123456789/7964.

Warrick, A.W., 2002. Soil Physics Companion. CRC Press LLC, Boca Raton, USA.

White, R.E., 2006. Principles and Practice of Soil Science. Blackwell Publishing, Oxford, UK.

WRB, I.W.G., 2014. World Reference Base for Soil Resources 2014. International Soil Classification System For Naming Soils And Creating Legends For Soil Maps. World Soil Resources Report No.106. FAO, Rome.

SUPPLEMENTAL FILES (MANUSCRIPT – I)

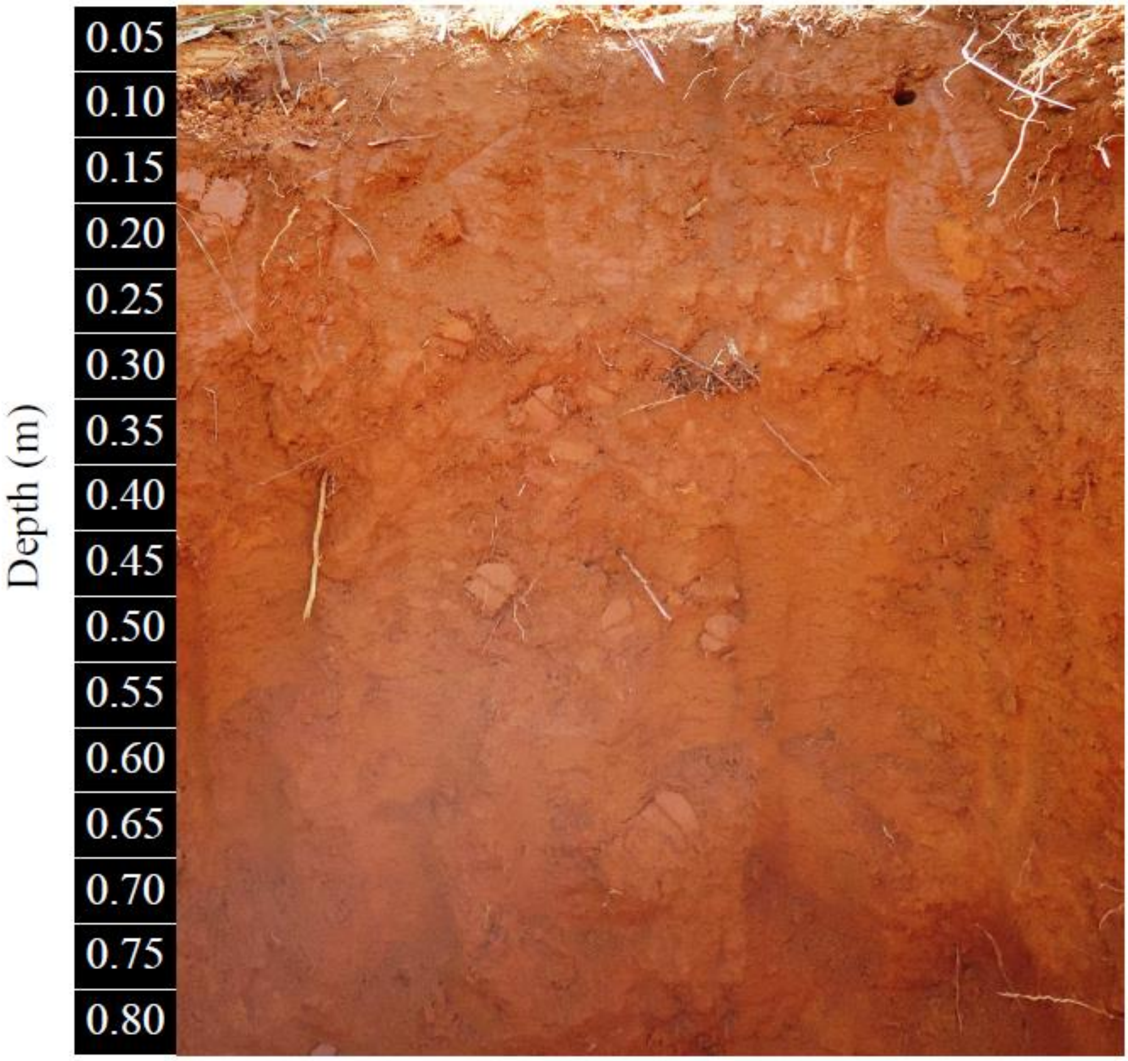


Figure 1. Cambissolo Háplico Tb distrófico (Santos et al., 2018); Typic Hapludept in Soil Taxonomy (Soil Survey Staff, 2014); Dystric Cambisols in WRB-FAO (World Reference Based, 2015)) of studied area.

Table 1. Soil profile description according to the methodology proposed by Tavares Filho et al. (1999).

Depth	Horizon	Deatails
(0 - 0.08m)	HzA	Very narrow due to excessive washing by rainwater with moderate block structure;
(0.08 - 0.33 m)	HzAB	With a moderate block structure;
(0.33 - 0.65 m)	HzBi	With a moderate block structure;
(0.65 - 0.85 m)	HzBC	A massive structure, soft-wet material. Presence of gneiss fragments from 0.80 m. Color enhancement from HzB to HzC;
(0.85 m+)	HzC,	A massive structure, soft-wet material.

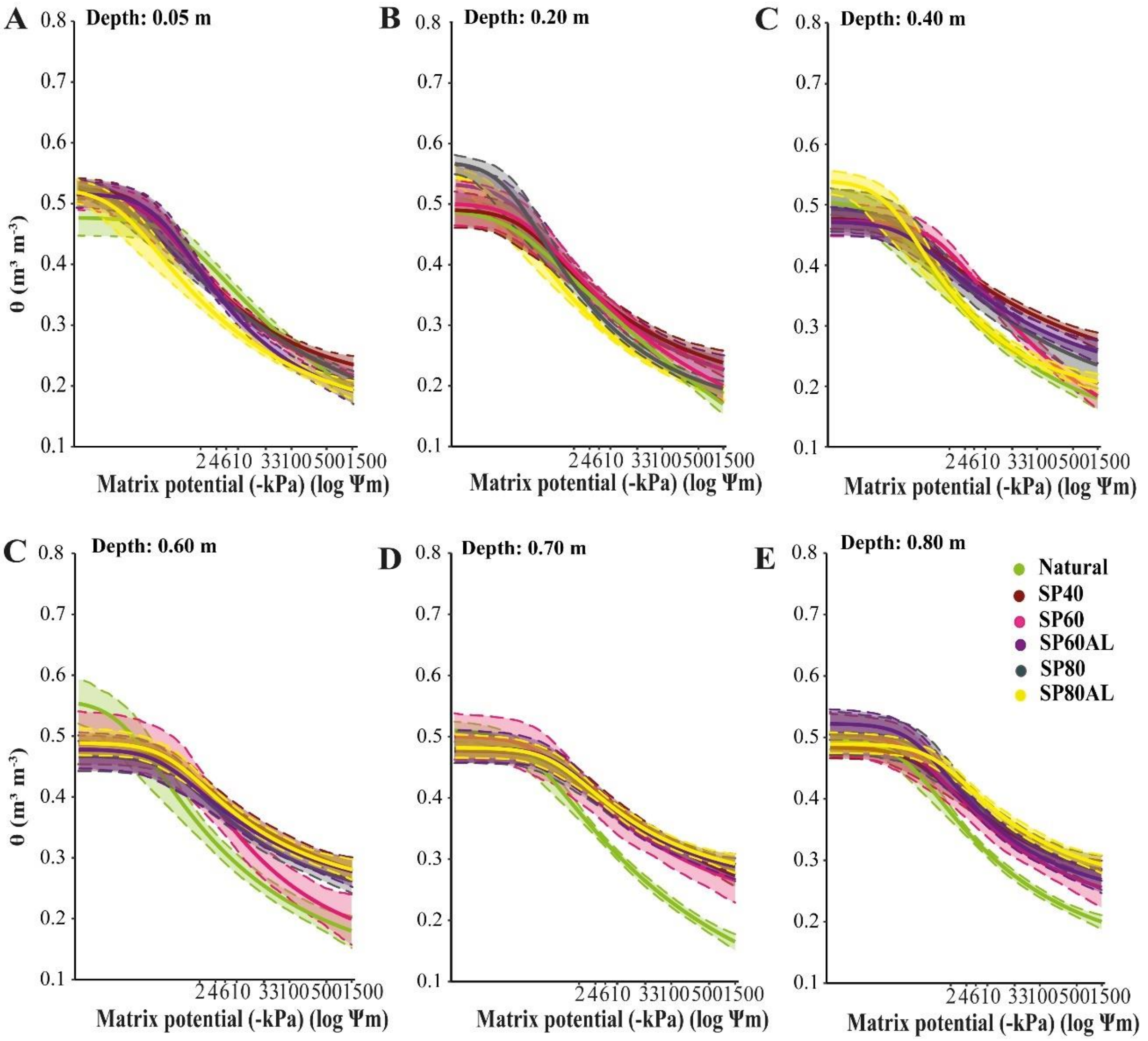


Figure 2. Water retention curves (WRCs), volumetric water content (m^3 m^{-3}) (θ) in the function of the matric potentials for different treatments: SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP80AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler; Natural a native savannah vegetation area from Cerrado biome and depths (0.05; 0.20; 0.40; 0.60; 0.70 and 0.80 m).

Table 2. Fitted parameters for soil water retention curves (van Genuchten, 1980) at different depths of a Cambisol under soil preparations and natural conditions.

Treatments	θ_S	θ_R	α	m	n	R^2
			0.05 m			
Natural	0.48	0.20	0.66	0.30	1.45	0.92
SP40	0.52	0.23	2.22	0.28	1.40	0.92
SP60	0.51	0.22	2.65	0.27	1.38	0.92
SP60AL	0.52	0.20	1.43	0.29	1.41	0.92
SP80	0.53	0.22	2.70	0.26	1.35	0.92
SP80AL	0.53	0.20	3.66	0.27	1.37	0.92
			0.20 m			
Natural	0.49	0.17	1.42	0.25	1.34	0.95
SP40	0.49	0.24	1.63	0.28	1.39	0.95
SP60	0.50	0.21	1.71	0.28	1.39	0.95
SP60AL	0.53	0.23	3.40	0.27	1.37	0.95
SP80	0.56	0.20	3.21	0.28	1.40	0.95
SP80AL	0.55	0.19	4.16	0.28	1.38	0.95
			0.40 m			
Natural	0.50	0.19	2.24	0.27	1.37	0.96
SP40	0.48	0.28	1.26	0.27	1.36	0.96
SP60	0.49	0.21	1.63	0.26	1.36	0.96
SP60AL	0.47	0.26	1.28	0.28	1.39	0.96
SP80	0.49	0.24	1.82	0.29	1.40	0.96
SP80AL	0.54	0.21	3.36	0.28	1.38	0.96
			0.60 m			
Natural	0.55	0.18	4.63	0.27	1.36	0.92
SP40	0.48	0.28	0.68	0.28	1.40	0.92
SP60	0.49	0.20	2.12	0.26	1.36	0.92
SP60AL	0.48	0.28	1.21	0.28	1.39	0.92
SP80	0.47	0.26	0.98	0.29	1.41	0.92
SP80AL	0.49	0.28	0.87	0.28	1.39	0.92
			0.70 m			
Natural	0.58	0.17	1.82	0.24	1.31	0.98
SP40	0.48	0.28	0.52	0.30	1.43	0.98
SP60	0.50	0.27	1.58	0.28	1.40	0.98
SP60AL	0.49	0.29	0.66	0.29	1.41	0.98
SP80	0.48	0.28	0.85	0.28	1.39	0.98
SP80AL	0.49	0.30	0.90	0.28	1.40	0.98
			0.80 m			
Natural	0.49	0.21	1.46	0.28	1.39	0.98
SP40	0.48	0.28	1.04	0.28	1.39	0.98
SP60	0.50	0.26	1.27	0.29	1.41	0.98
SP60AL	0.53	0.27	1.46	0.29	1.41	0.98

SP80	0.51	0.28	1.06	0.30	1.43	0.98
SP80AL	0.49	0.30	0.54	0.30	1.42	0.98

θ_S: (m^3 m^{-3}) volumetric water content (m^3 m^{-3}) at the saturation point (Ψm 0 kPa); θ_R: (m^3 m^{-3}) volumetric content of residual soil water, the same as PWP: permanent wilting point, (Ψm -1500 kPa); α, m and n are the fitted empirical parameter obtained by SWRC software; R^2: coefficient of determination. SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP80AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler; Natural a native savannah vegetation area from Cerrado biome.

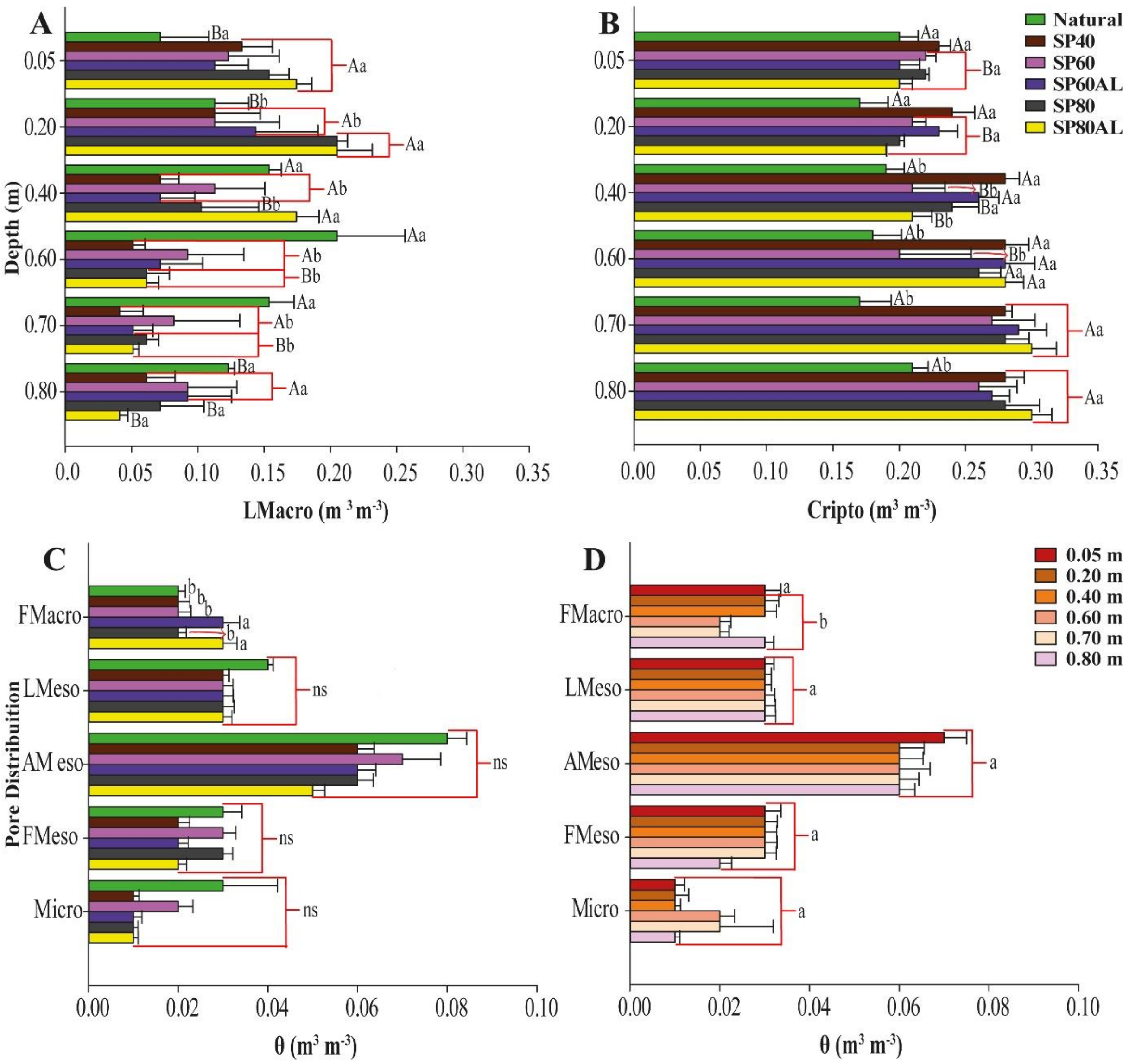


Figure 3. Pore size distribution with significant interaction between treatment and depth for LMacro (A) and Cripto pores (B); comparison between the average values of each pore distribution class only between treatments regardless of depth (C) and only between depths irrespective of treatment (D). For A and B, means followed by the same lowercase letter do not differ from each other for treatments within the same depth. By the same uppercase letter, they do not differ from each other for depths within the same treatment by the Skott-Knott test ($p < 0 .05$). As for C and D, means followed by the same lowercase letter they do not differ for treatments (C) and depths (D) by the Scott-Knott test ($p < 0.05$), ns: not significant by the F test ($p < 0.05$). SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional

liming (SP80AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler; Natural a native savannah vegetation area from Cerrado biome. LMacro: large macropores (> 147 µm); FMacro: fine macropores (147-73 µm); LMeso: large mesopores (73-49 and 49-29 µm); AMeso: average mesopores (29-9 and 9-2.9 µm); FMeso: fine mesopores (2.9-0.6µm); Micro: micropores (0.6-0.2 µm); Cripto: criptopores (> 0.2 µm).

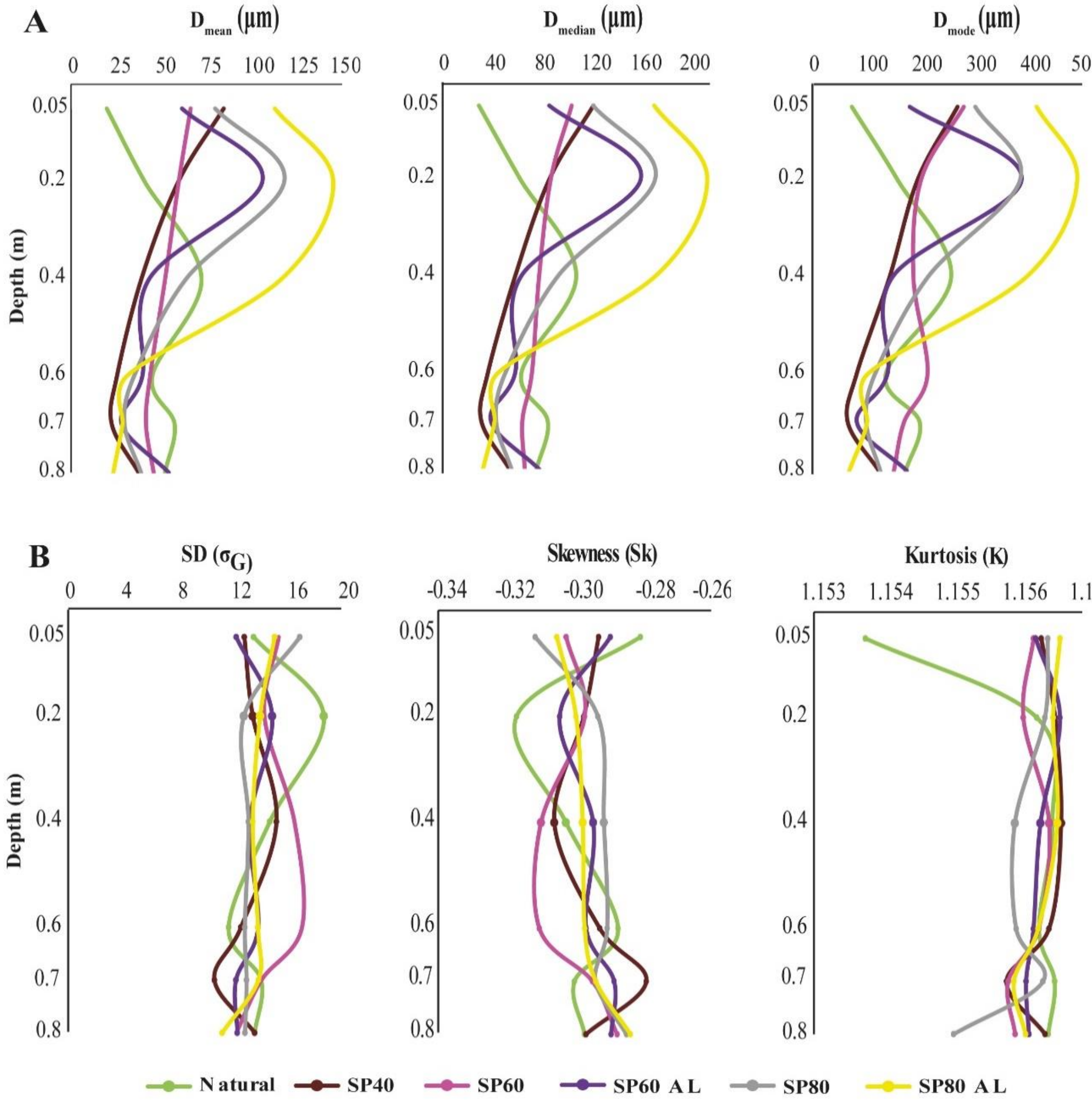


Figure 4. Location (A) and shape (B) parameters for the normalized pore volume distribution function for the different soil preparations. D_{mean}, D_{median}, and D_{mode} refer to the mean, median and modal values, respectively, of d_e (equivalent pore diameter); SD standard deviation (SD - σ_G), *Sk* skewness (asymmetry), and *K* kurtosis (peak). SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP80AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler; Natural a native savannah vegetation area from Cerrado biome.

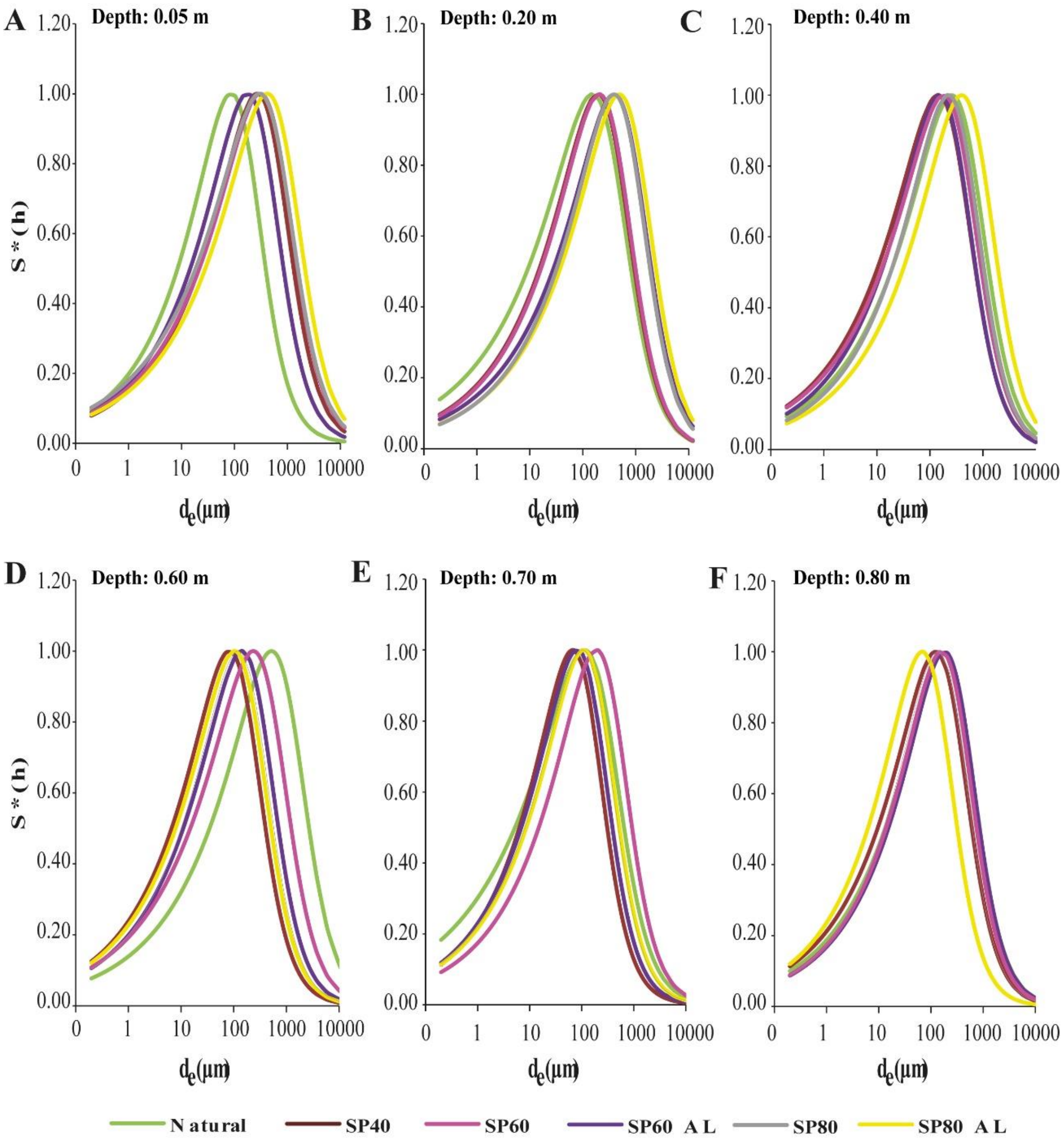


Figure 5. Normalized pore volume distribution function as a function of equivalent pore diameter for the different treatments and depths of Cambisol. SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP80AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler; Natural a native savannah vegetation area from Cerrado biome.

MANUSCRIPT – II

(Manuscript formatted according to Soil and Tillage Research Journal guidelines)

Soil structure, antioxidant enzymes, and root system of rainfed coffee through deep tillage strategies

Abstract: Deep tillage is a promising solution to reduce drought effects for crops in dense soils. With climate change worsening water scarcity, it is crucial to understand how deep tillage improves soil structure for root growth and water storage and absorption, benefiting sustainable agriculture. This study aims to evaluate the association between different strategies of deep tillage and chemical amendments in the planting furrow, focusing on soil physical properties and responses by coffee plants. The experiment was conducted on a commercial farm in Nazareno, Minas Gerais, Brazil, in a Cambisol area with a clay loam texture. A randomized block design experiment was performed with three blocks, and the following five soil preparations were tested: SP40: soil preparation with a furrower was used to open the planting furrow at 0.40 m depth with conventional fertilization; SP60: Big Mix (Soil homogenizer) was applied at 0.60 m with conventional fertilization and with chemical amendments by additional liming (SP60AL); SP80: Soil homogenizer was employed at 0.60 m, followed by a Dreno (subsoiler) at 0.80 m with conventional fertilization and with additional liming (SP80AL). After five years, undisturbed soil samples were collected at depths 0.00-0.05; 0.15-0.20; 0.35-0.40; 0.55-0.60; 0.60-0.70; 0.75-0.80 m in metallic rings and the format of blocks both at the experimental area and an area apart from the testing site under native savannah vegetation from the Cerrado biome (Natural). The experimental site analyzed soil penetration resistance (PR), bulk density (BD), root system growth variables, and chemical element contents with soil water content evaluated from October 2019 to March 2021, and the antioxidant enzymatic system of coffee leaves investigated during the dry (September 2020) and wet (January 2021) seasons. Analysis of variance and the Scott-Knott and Dunnett tests ($p < 0.05$) were applied to analyze the data. The surface mapping of the following PR, root variables, element contents, and the spatiotemporal mapping of soil water content were examined by kriging via geostatistical analysis. The results indicated that SP60 improved the soil's structural quality by enhancing aggregate stability and reducing PR and BD at various depths. The planting furrow opened at a depth of 0.60 m facilitated remarkable root development in coffee plants, promoting better water absorption along the soil profile. This condition led to increased antioxidant activity, with a reduction in hydrogen peroxide and lipid peroxidation, especially during dry periods. On the other hand, SP80AL increased water content at depth during dry periods. It facilitated homogenous root development in coffee plants up to 0.70 m due to lower aluminum concentration and better distribution of calcium and magnesium. While this soil preparation approach showed benefits for coffee cultivation in dense Cambisols, it was not as profitable as SP60. Despite the lower antioxidant activity in SP80AL, SP60 demonstrated better drought tolerance due to improved soil physical properties and acclimatization of coffee plants under dense Cambisols and dry conditions. Mapping all analyzed variables was crucial in understanding the effects of different deep tillage strategies, providing valuable insights for future soil preparation decisions for coffee growers.

Keywords: Additional liming; Antioxidant enzymes; Deep tillage; Soil moisture; Soil structure; Penetration resistance; Root system.

1. Introduction

Coffee is a globally consumed and traded beverage, with Brazil being the leading producer. However, climate change has negatively impacted coffee growth and production, leading producers to seek solutions to increase the drought tolerance of crops. In Minas Gerais, the largest coffee-producing region in Brazil, where cultivation and approximately

70% of the nation's coffee production occurs. However, water scarcity resulting from prolonged dry periods, including reduced and irregular rainfall, high temperatures, and early frost events, hinders the growth of coffee plants, especially during crucial stages like flowering and fruit formation. Consequently, a lower production is anticipated for 2022 than the previous year (Mendes et al., 2022; Jawo et al., 2022; Conab, 2022).

Decision-making in the coffee farming sector in Minas Gerais has prioritized conservationist soil preparation practices that focus on understanding and managing the water resource dynamics of the soil (Carducci et al., 2014; Carducci et al., 2015). This approach, especially in dense soils like Cambisols, involves liming in deeper layers to improve the soil structure (Silva et al., 2021; Barbosa et al., 2020; Serafim et al., 2013a). The goal is to promote chemical and physical improvements in the soil profile, which can significantly increase coffee productivity (Serafim et al., 2013b).

Cambisol stands out from other soils due to its unique characteristics, including an incipient (weakly structure development degree) horizon B and high silt content, which result in poor drainage (Bortolanza; Klein, 2016; Soil Survey Staff, 2014; Santos et al., 2018). This soil type is challenging for coffee cultivation due to physical restrictions, such as shallow effective depth, high natural density, and nutrient deficiencies. Additionally, coffee plants have a lower tolerance to environmental factors, particularly climate conditions (Barbosa et al., 2020). To overcome these challenges, deep tillage management practices, such as subsoilers and scarifiers (Ning et al., 2022), can break up compacted layers and promote root development along the soil profile. This soil preparation method improves water accessibility for rainfed coffee production (Silva et al., 2021).

Agronomic and environmental processes like organic carbon dynamics (Rabot et al., 2018) and soil organisms' activities (Havlicek; Mitchell, 2014) are closely linked to soil structure. Improving soil structure is crucial for optimizing crop yields and overall system vitality (Serafim et al., 2013b). Structural soil quality refers to the soil's ability to resist external stresses, including mechanical and hydric factors. Enhancing soil structural integrity involves the formation of stable aggregates that prevent deterioration and improve water circulation (Barbosa et al., 2020; Silva et al., 2021; Ning et al., 2022). Effective conservationist management practices prioritize accessible water, nutrient distribution, acidity correction, and calcium availability in the Cambisol profile, creating a favorable environment for coffee root development (Teixeira et al., 2018; Barbosa et al., 2020). A well-established root system supports plant growth (Carducci et al., 2014; 2015; Silva et al., 2016b), with magnesium playing a significant role in the plant's physiological processes (Faiz et al., 2022). Mapping and monitoring soil attributes in coffee cultivation provides valuable information for precision agriculture and decision-making by coffee producers (Bazame et al., 2021).

Under water stress, plants limit their physiological processes, leading to increased generation of reactive oxygen species (ROS), which can be toxic and damage the plant's normal cell functions (Cherono et al., 2021). Therefore, to enhance tolerance to adverse conditions like drought, plants increase the enzymatic activities of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) (Campos et al., 2019). This evaluative enzymatic criterion is crucial as water scarcity has caused significant losses in coffee production (Cherono et al., 2021). Therefore, understanding coffee plants' drought resistance strategies is essential (Campos et al., 2019; de Sousa et al., 2022).

Thus, this study hypothesizes that deep tillage strategies, including soil preparation and subsoiling, combined with additional liming, will improve the soil's physical quality and positively affect penetration resistance, root development, and drought tolerance mediated by antioxidant enzymes. The aim is to evaluate the association between different strategies of deep tillage and chemical amendments in the planting furrow in improving soil physical quality to root development and mitigate drought stress evaluated through the plant antioxidant system.

2. Material and Methods

2.1. Location and characterization of the experimental site

The study was conducted on an experimental coffee plantation located in the municipality of Nazareno, belonging to the Alto Rio Grande Basin, inserted into the crystalline surface of the Alto Rio Grande with geographical coordinates latitude 21° 10' 52″ S and longitude 44° 39′ 04″ W (Figura 1) at an average altitude of 935 m. Regarding the historical context of the experimental area, pasture originally covered the area before introducing coffee. According to the Brazilian soil classification system, the soil at the study site was classified as Cambissolo Háplico Tb distrófico (Santos et al., 2018). This classification corresponds to Typic Hapludept in Soil Taxonomy (Soil Survey Staff, 2014) and Dystric Cambisol (WRB, 2014) - the official classification adopted in the present study. The soil in Horizon Bi had a clay loam texture (Clay: 34 g kg^{-1}; Silt, 23 g kg^{-1}; Sand, 43 g kg^{-1}) with a moderate block structure. The parent material consisted of pelitic rocks and quartzite on granite-gneiss. The soil was chemically and physically characterized before the experiment (Table 1). The local climate was classified as Cwb, according to Köppen (1936) (Figure 1), indicating a humid temperate climate with dry winter and moderately hot summer. The average annual temperature is 18.5°C, and the rainy season occurs from November to March, with an average yearly rainfall of 1350 mm.

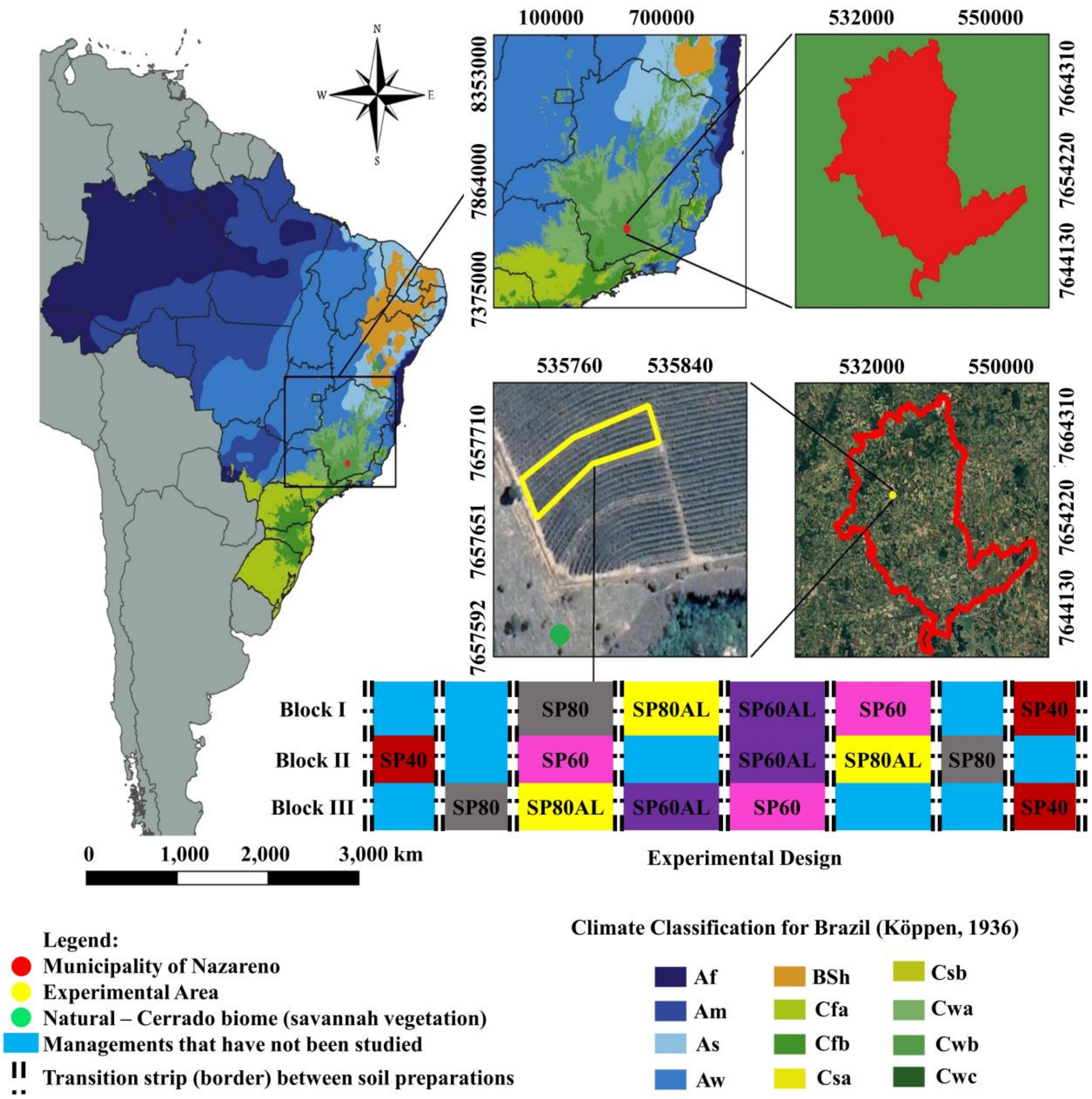


Figure 1. Location and design of the experimental area in UTM zones. SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler.

Table 1. Soi chemical properties in the soil profile before coffee crop planting in 2015.

		Depth (m)			
		0.00-0.20	0.20-0.40	0.40-0.60	0.60-0.80
pH	(H_2O)	5.1	5.5	5.8	5.7
K	mg dm^{-3}	22.7	16.7	11.3	12
P		0.4	0.3	0.1	0
Na		2	2.7	2	2
Ca	$cmol_c$ dm^{-3}	0.4	0.3	0.3	0.4
Mg		0.1	0.1	0.1	0.1
Al		0.2	0.1	0	0
H+Al		3.2	2.8	1.9	1.8
SB		0.6	0.4	0.4	0.5
t		0.8	0.5	0.4	0.5
T		3.7	3.2	2.3	2.4
V	%	15.9	13.1	18.9	22.7
m		28.8	19.9	0	0
M.O.	dag kg^{-1}	2.3	1.9	1.5	1
P-Rem	mg l^{-1}	13.4	8	3.4	3.1
Zn	mg dm^{-3}	0.9	0.6	1	0.7
Fe		61.1	40.3	27.2	32
Mn		5.8	2.3	1.6	2.5
Cu		1.8	1.7	1.5	1.5
B		0.7	0.2	0.2	0.1
S		6	5.1	5	4.6
Clay	g kg^{-1}	33	33	35	37
Silt		16	23	22	27
Sand		51	44	43	36

pH: hydrogen potential determined in water; OM: Organic Matter; SB: Sum of bases; t: effective cation exchange capacity; T: potential cation exchange capacity; m: aluminum saturation; V: Base saturation; P-Rem: Remaining phosphorus. Adapted from Barbosa et al. (2020).

2.2. Soil preparation

The soil was chemically corrected based on the properties listed in Table 1. Then, dolomitic limestone was applied at 3 Mg ha^{-1} (1.5 g dm^{-3}) 60 days before planting. The limestone, with a neutralizing power of 87%, CaO content of 39.7%, and MgO content of 13.38%, was incorporated into the soil using a harrow implement across the entire area.

Five soil preparation were implemented for planting the coffee crop in a uniform area. These strategies included one traditional preparation, two focused on deepening the planting furrow, and two involved chemical amendments by additional liming and deep furrow opening. The preparations applied were furrower (SP40), soil homogenizer (SP60), soil homogenizer + additional liming (SP60AL), soil homogenizer + subsoiler (SP80), and soil homogenizer + subsoiler + additional liming (SP80AL) (Figure 2A).

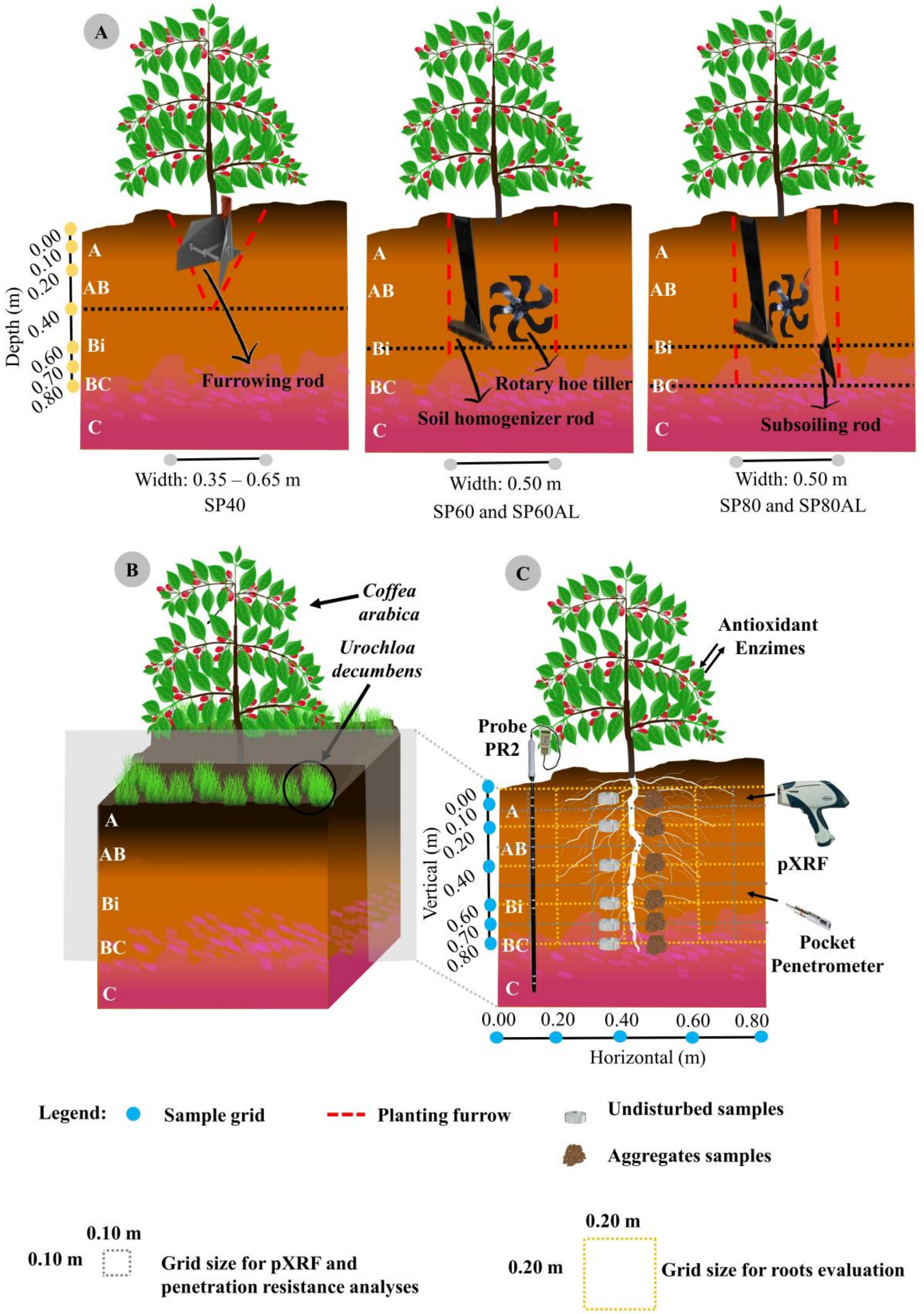


Figure 2. Schematic representation of the Cambisol with the different soil preparation strategies aly with their respective agriculture implements (A); Representation of the different soil preparations with the different agricultural implements used for the opening of the

planting furrow under the coffee crop in the experimental area (B); Representation of the collection of samples with preserved structure (structural physical-hydric quality and aggregates) in the planting furrow area follow by the penetration resistance, root system, soil moisture monitoring, pXRF evaluation and plant measurements by the NDVI (C); Representation of the soil preparation strategies with different agriculture implement (C). Adapted from Silva et al. (2021). SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler.

The furrower implement, with a width of 0.35 to 0.65 m, creates furrow at a depth of 0.40 m, requires a 60 hp tractor, and weighs approximately 105 kg. The Big Mix equipment, equipped with a rotary hoe tiller and a fertilizer box with a volume of 270 dm^3, homogenizes the soil effectively at a width of 0.50 m and a depth of 0.60 m. It needs an 85-hp tractor with super-reduced gear, operates at a speed of 0.6 to 1 km per hour, and weighs 450 kg (Mafes, 2017). The Dreno agricultural tool is designed to remove physical impediments in the soil, effective up to a depth of 0.80 m and capable of reaching 0.90 m. It requires a tractor power above 180 hp, operates at speeds of up to 6 km per hour, and has a load capacity of 450 kg or 1.2 tons (Mafes, 2017). Furrows opened to a depth of 0.40 m were closed using a two-rod subsoiler at 3 to 5 km per hour after the furrower had passed. For furrows opened to depths of 0.60 and 0.80 m, the Big Mix equipment utilized a specific attached tool to close them (Mafes, 2017).

All soil preparations followed coffee-growing recommendations for fertilization (Guimarães et al., 1999). However, only SP60AL and SP80AL received 200g of dolomitic limestone per linear meter of the furrow (additional liming), based on data from table 1. This preparation strategy aimed to increase the soil's base saturation to 70%. The additional liming was effectively mixed and incorporated from 0.20 to 0.60 m depth in each furrow by the soil homogenizer, utilizing the rotary hoe tiller and the coupled fertilizer box as described in Mafes (2017). Topdressing fertilizations were performed thrice, with the first application in February 2016, using 0.004 kg of N and K_2O per plant. The interval of twenty days between applications aimed to improve nitrogen utilization efficiency and reduce losses, particularly leaching.

Considering the susceptibility of the Cambisol group to water erosion in undulating terrain, conservation practices were implemented to mitigate its effects. Terracing, through mechanical methods, and the cultivation of *Brachiaria decumbens* L. (*Syn. Urochloa*) between crop rows, using the vegetative methods, were combined.

To evaluate the effects of soil preparations on coffee plantations, particularly after the completion of the second cycle in 2017 (Barbosa et al., 2020; Silva et al., 2021), a series of crop management were implemented. These managements aimed to promote optimal growth and development of coffee plants, including applying topdressing fertilizer. The objective was to assess the subsequent impacts on soil quality and crop performance. For the 2018-2019 crop, each plant received 0.66 kg of liming, followed by 0.062 kg of N and K_2O and 0.013 kg of P_2O_5. However, for the 2019-2020 crop, only 0.049 kg of N and K_2O per plant was applied. This crop year was associated with evaluating the performance of this Cambisol under coffee cultivation, marking the end of the fifth cycle.

2.3. Experimental Arrangement

The experimental design consisted of randomized blocks with five soil preparers (SP40, SP60, SP60AL, SP80, SP80AL). Each experimental plot comprised crop strips measuring 10.8 m wide and 84 m long (907.2 m²). Within each plot, there was a planting line of 10.5 m, containing fourteen plants for each studied soil preparation. The experiment was replicated in three blocks (Figure 1). The coffee cultivar was Catuaí Vermelho - IAC 99 (*Coffea arabica* L.), planted in December 2015. The spacing between plants was 0.75 m, and the distance between planting lines was 3.6 m, resulting in a density of 3,703 plants per hectare. Border rows were included in each experimental plot, consisting of one external row on the left and right sides and one row between each soil preparer within the testing area (nine rows in total) (Figure 1). These border rows were not used for soil collection or plant evaluation to minimize environmental effects and plot interaction. Data collection was conducted randomly within the central plot strips, focusing on soil aggregates, root systems, penetration resistance, element contents, water content monitoring, and antioxidant enzyme levels in leaves.

2.4. Soil physical characterization

In December 2020, five years after coffee implantation, undisturbed soil core samples were collected from soil trenches in the experimental coffee area and a Cerrado biome native savannah vegetation area, apart from the testing site, referred to as Natural (Figures 1 and 2). The samples were collected at different depths (0.00-0.05; 0.15-0.20; 0.35-0.40; 0.55-0.60; 0.60-0.70; 0.75-0.80 m) in metallic rings (0.063 m in diameter and 0.025 m in height), using an Uhland-type sampler for the soil physical-hydric characterization and in the format of soil blocks to evaluate soil aggregates stability.

Soil trenches were dug with a 0.20 m distance from the coffee plant trunk to the trench wall, ensuring a horizontal reach of 0.80 m within the canopy. At each of the six depths, one ring and soil block were collected for each of the five soil preparations and within each of the three blocks. This sampling resulted in 90 samples for aggregate and physical-hydric characterization. In addition, 18 samples were collected, consisting of three metallic rings and soil blocks from each specified different depth in the Natural area. The study encompassed six treatments (SP40, SP60, SP60AL, SP80, SP80AL, and Natural), resulting in 108 samples with preserved block structures and another 108 metallic ring samples.

Aggregate samples were air-dried and sieved. First, the aggregate fractions greater than 8 mm and retained on the 4.76 mm sieve were used (Grohmann, 1960). Then, 25g of aggregates were submitted to pre-wetting (Teixeira et al., 2017) and subsequently to submerged sieving in water with vertical agitation (Yoder, 1936). Finally, were calculated the mean geometric diameter (MGD) and the index of aggregate stability (IAS) also according to (Teixeira et al., 2017).

The undisturbed metallic ring soil samples were submitted at gradual saturation using distilled water. After saturation, the samples were submitted to matric potentials (Ψ_m) of -2, -4, -6, -8, and -10 kPa, in suction units and Ψ_m of -33, -100, -500, and -1500 kPa in the Richards extractor (Teixeira et al., 2017). After reaching equilibrium, the samples were weighed and placed in a forced circulation oven at 105 - 110ºC for 24 hours.

Subsequently, soil density (BD) was calculated using the volumetric ring methodology (Teixeira et al., 2017). Then the available water capacity was calculated and estimated by the water content at the field capacity (θ_{FC}) and by the water content at the permanent wilting point (θ_{PWP}) (Silva et al., 2015), being the water content in the field capacity adopted by the Ψm -10 kPa, as also assumed by Lima et al. (2010) when studying Cambisol under coffee cultivation.

2.5. Soil penetration resistance spatial variation

The Soil Penetration Resistance (PR) was measured manually using a pocket penetrometer CL-700 (Soil test 2205 Lee Street, Chicago, Illinois, USA). This equipment has a fixed, non-rotating cylindrical probe of 3.0 mm, carefully inserted perpendicularly into the soil up to the reference mark contained in the penetrometer. The reading was recorded in kgf cm^{-2} (Ajayi et al., 2009). The PR measurement was done in the same soil trenches opened for the root development study at the experimental area using another grid consisting of 0.10 x 0.10 m squares. The gravimetric soil water content U (g g^{-1}) was also determined for each square in the grid, with 64 total samples of moisture and PR readings (8 depths x 8 measurements) for all treatments.

After reading in kgf cm^{-2} necessary to penetrate the soil, these were converted into MPa multiplied by 0.98066 since 1.0 kgf cm^{-2} equals 0.98066 MPa. For a better understanding of the PR behavior related to the gravimetric water content at the moment of this measurement, for each soil preparation and depth was plotted U_{10kPa}, the gravimetric water content in the field capacity and calculated the BD.

2.6. Root system development

Soil trenches with 0.70 m (width) x 0.80 m (length) x 0.80 m (depth) dimensions were opened for the root development study using the cultural profile method (Jorge; Silva, 2010). The vertical wall of the trench was maintained at 0.10 m far from the plant trunk under the coffee plant canopy projection, from which the scarification of up to 0.05 m towards the interior of the soil was done to expose the roots. The roots received a thin layer of white paint to perfectly contrast the roots and soil (Carducci et al., 2014; Carducci et al., 2015).

A grid with 0.20 x 0.20 m squares was placed precisely parallel to the trench wall and in front of the roots. Then, using a photographic camera with 14 megapixels resolution, 2D digital images were obtained. Considering the maximum furrow preparation depth of 0.80 m and the trench dimensions limits were generating a total of 16 sampling points. The images were processed and aligned in the free software ImageJ and later submitted to the SAFIRA program (Jorge; Silva, 2010), generating variables of root number (RN), root volume (RV) (mm^3), root surface area (RSA) (mm^2), root length (RL) (mm), and root diameter (RD) (mm). The Ø of roots was classified according to Motta et al. (2006) as fine roots (Ø <1 mm), medium roots (1 > Ø < 3 mm), and thick roots (Ø > 3 mm in diameter).

2.7. Soil water content monitoring

A profile probe PR2/6-SDI-12 (Delta-T Devices Ltd., Cambridge, UK) was used to monitor the soil water content vertical distribution. This monitoring is characterized as a non-destructive evaluation method of temporal variability of the soil moisture applied for the following depths: 0.10, 0.20, 0.30, 0.40, 0.60, and 1 m. Four access tubes were installed in the experimental area for each treatment positioned between the coffee plants in the planting row at the middle of the furrow. The readings were carried out fortnightly, starting in October 2019 and ending in March 2021. They aimed to identify periods and depths of water deficit and understand the soil water storage variability and its consumption by the coffee plant, as also proposed by Silva et al. (2015), however, focusing on different deep tillage strategies.

The profile probe readings related to the permittivity of the water content of the soil, a measure of a material's response to polarization in an electromagnetic field, resulting in a stable voltage output in millivolts (mV), were transformed into volts (V) and then converted into soil moisture ($m^3\ m^{-3}$) by polynomial conversion combined with soil calibration:

$$\theta_V = \left[1.125 - 5.53V + 67.17V^2 - 234.42V^3 + 413.56V^4 - 356.68V^5 + 121.53V^6\right] - a_0/a_1$$

(Equation 1)

Where: V is the value resultant in a stable voltage output in volts, a_0 and a_1 are the calibration coefficients, being $a_0 = 1.6$ and $a_1 = 8.4$ related to mineral soils with the organic matter content below 7% and bulk density above 1.0 Mg m^{-3} (Delta-T Devices, 2016).

After obtaining the soil moisture values, a map of the monitoring of moisture over time (MMOT) was built and from it. This data was calculated based on the soil physical-hydric data described and determined in the 2.4 section for the available water classification, considering ($\theta > 0.35$ m^3 m^{-3}) being easily drainable water, ($0.35 < \theta > 0.25$ m^3 m^{-3}) related to plant-available water, and ($\theta < 0.25$ m^3 m^{-3}) characterized like strongly retained water.

2.8. Chemical elements contents obtained by pXRF in soil depth

The soil chemical element contents along the soil profile were determined using the same grid for PR evaluation. Soil samples were collected inside of each grid square at intervals of 0.10 m both horizontally (0.80 m) and vertically (0.80 m), summing 64 total samples (8 depths x 8 samples) across the entire soil profile. These 64 soil samples were air-dried and sieved using a 2 mm mesh. These samples, after preparation, were each examined by pXRF Bruker, model S1 Titan LE. This equipment contains a Rh tube of X-rays of 50 keV and 100 µA and a silicon drift detector with a resolution of < 145 eV. To validate the precision of pXRF analyses, certified samples from the pXRF manufacturer (check sample) and the National Institute of Standards and Technology (NIST) (2710a and 2711) were scanned, and the obtained results were compared with their certified contents. The recovery values (content obtained by pXRF/certified content) for the check sample, 2710a and 2711 were measured for various elements (Al - 0.91/1.34/0.49; Si - 0.91/1.53/0.85; Fe - 0.91/0.44/1.09; K - 0.88/0.66/0.68; Ca - 0/1.62/0.44; Ti - 0/0.74/0.95; Zr - 0/1.31/0). A value of 0 indicates the absence of a certified value or the equipment's lack of results for that element. Each soil sample was analyzed in triplicate for 60 seconds using Geochem software in Trace mode (dual soil) (Weindorf; Chakraborty 2016).

2.9. Antioxidant system evaluation

Coffee leaves were evaluated in two periods, dry (September/2020) and wet (January/2021), for all coffee plants, in each plot of the planting line (12 useful plants) of all the soil preparations studied. In this way, in each period, for the evaluation of the enzymatic activities of the antioxidant system, leaves of the third pair completely expanded from top to bottom were collected, encompassing both sides of the plant. These leaves were wrapped in aluminum foil and immersed in liquid nitrogen to preserve their activity.

Regarding the analysis of antioxidant enzymatic activity, the leaves were macerated in a cooled mortar with the aid of liquid nitrogen using 100 mg of PVPP (antioxidant) and stored at -80º C for the determination of ascorbate peroxidase (APX), catalase (CAT), superoxide dismutase (SOD), apart from hydrogen peroxide, lipid peroxidation, and total protein.

For the activities of ascorbate peroxidase APX, EC:1.11.1.11 (Nakano and Asada, 1981), catalase - CAT, EC:1.11.1.6 (Havir and McHale, 1987) and superoxide dismutase - SOD, EC 1.15.1.1 (Giannopolitis and Ries, 1977), 0.2 g of frozen leaf tissue was weighed and mixed with 1.5 mL of potassium phosphate buffer solution (0.1 mol L^{-1}, pH 7.8 + 0.1 mol L^{-1} EDTA, pH 7.0, 0.01 mol L^{-1} ascorbic acid, and 22 mg polyvinylpolypyrrolidone-PVPP). The suspension was centrifuged at 14.000 g for 10 min at 4° C (Biemelt et al., 1998), and the supernatant was used. To guarantee the quality of this analyze, the enzyme extraction was performed on the day of analysis to avoid oxidation of the enzyme extract and prepared at 0 - 4º C. In addition, the analyzes were performed in triplicate and adopted the use of two blanks in each reading plate, Epoch® Micro-plate Spectrophotometer (BioTek, United

States), as described in de Sousa et al. (2022).

Hydrogen peroxide and lipid peroxidation (malonaldehyde) were also determined from 0.2g of frozen leaf tissue macerated in liquid nitrogen, homogenized in 5 mL trichloroacetic acid (TCA), and centrifuged at 12,000 g for 15 min at 4º C, using the supernatant. Thus, the methodology proposed by Loreto and Velikova (2001) was adapted from Velikova et al. (2000) for hydrogen peroxide, while for lipid peroxidation, the methods described in Silva et al. (2020). Protein extraction was based on Bradford (1976) and Zanandrea et al. (2010), all of which were analyzed according to the procedures also described by de Sousa et al. (2022).

2.10. Data analysis

The soil variables data were treated as a split plot with two factors soil preparations (plot) x depths (split-plot). The traditional soil preparation (SP40) was treated as a reference preparer, and Natural was treated as a reference area to evaluate the effects of the other soil preparations, SP60, SP60AL, SP80, and SP80AL. For the coffee leaf evaluation data, SP40 was also treated as a reference preparer, which in this case, was a simple factorial only associated with the deep preparation responses. An analysis of variance was performed to compare the treatments studied, and when significant, the Scott-Knott ($p < 0.05$) test was applied to compare the mean values for soil aggregates. Specifically for antioxidant enzyme activity, the Scott-Knott test was applied to compare the soil prepares (SP60, SP60AL, SP80, SP80AL) between then, and the Dunnett test ($p < 0.05$) test was applied to compare the prepares described previously with the SP40 using the R statistical program (R Core Team, 2021).

Root data processed by the SAFIRA program was considered the maximum value for the NR, the average for RD, and the sum for RV, RSA, and RL to guarantee greater accuracy of the root variables under each square of the sample grid. With the results obtained in each sampling grid unit, spatial analyses of the root system, PR, and soil elemental contents were conducted via interpolation through the Multilevel B-splines (Lee et al., 1997) using the software QGIS 3.16.13 (QGIS Development Team, 2021). Only RP maps, BD U (%), and U_{FC} (%) data were analyzed and processed specifically for the physical characterization of this Cambisol.

The soil water content maps were generated by the Surfer software version 13, using the kriging module to interpolate the values (Usman et al., 2022) associated with the spatiotemporal dependence (Silva et al., 2015). The surface response was generated in Surfer 13 and imported into a geographic information system considering the following water content classes: < 0.05; 0.05 - 0.10; 0.10 - 0.15; 0.15 - 0.20; 0.20 - 0.25; 0.25 - 0.30; 0.30 - 0.35; 0.35 - 0.40 and > 0.40 $m^3 m^{-3}$ (volumetric water content), related to the minimum and maximum moisture of the dataset studied (PR2/6-SDI-12 readings).

The surface maps were purposed to visualize better the root variables distribution and soil penetration resistance along the soil profile for the different soil preparations after five years from the coffee plantation. On the other hand, the water content maps are intended to evaluate the variability in different soil preparations assessed under the period (October/20219 - March/2021) considered. For soil element contents mapping, only elements associated with the chemical amendments were selected, that is, elements related to the additional liming practice and the soil acidity condition (Ca, Mg, and Al), which will allow a better understanding of their disposition and concentrations along the soil profile and understanding the efficiency of this chemical amendments over time.

3. Results and Discussion

3.1. Soil penetration resistance spatial variation

Regardless of the soil tillage preparation, the penetration resistance (PR) tends to be lower on the surface and increases with depth in the soil profile. This trend is also observed for soil bulk density (BD) (Figure 3). The findings indicate that PR varies depending on the type of implement used for furrow preparation. Shallow implements like the furrower increased PR in the 0.10 to 0.25 m layer. More profound tools, such as rotary hoe tiller and subsoiling rod, showed higher PR values starting from 0.25 m and 0.40 m, respectively (Figure 3). In a previous study conducted in the same experimental area, Silva et al. (2021) confirmed that the soil preparation equipment used in this study caused compaction at the bottom of the furrow, below the equipment's working depth. The authors assessed this compaction through a decrease in hydraulic conductivity, which indicates the operational error when machinery operates beyond the soil's friability zone. Such structural damage can negatively affect the growth of coffee plants (Barbosa et al., 2020).

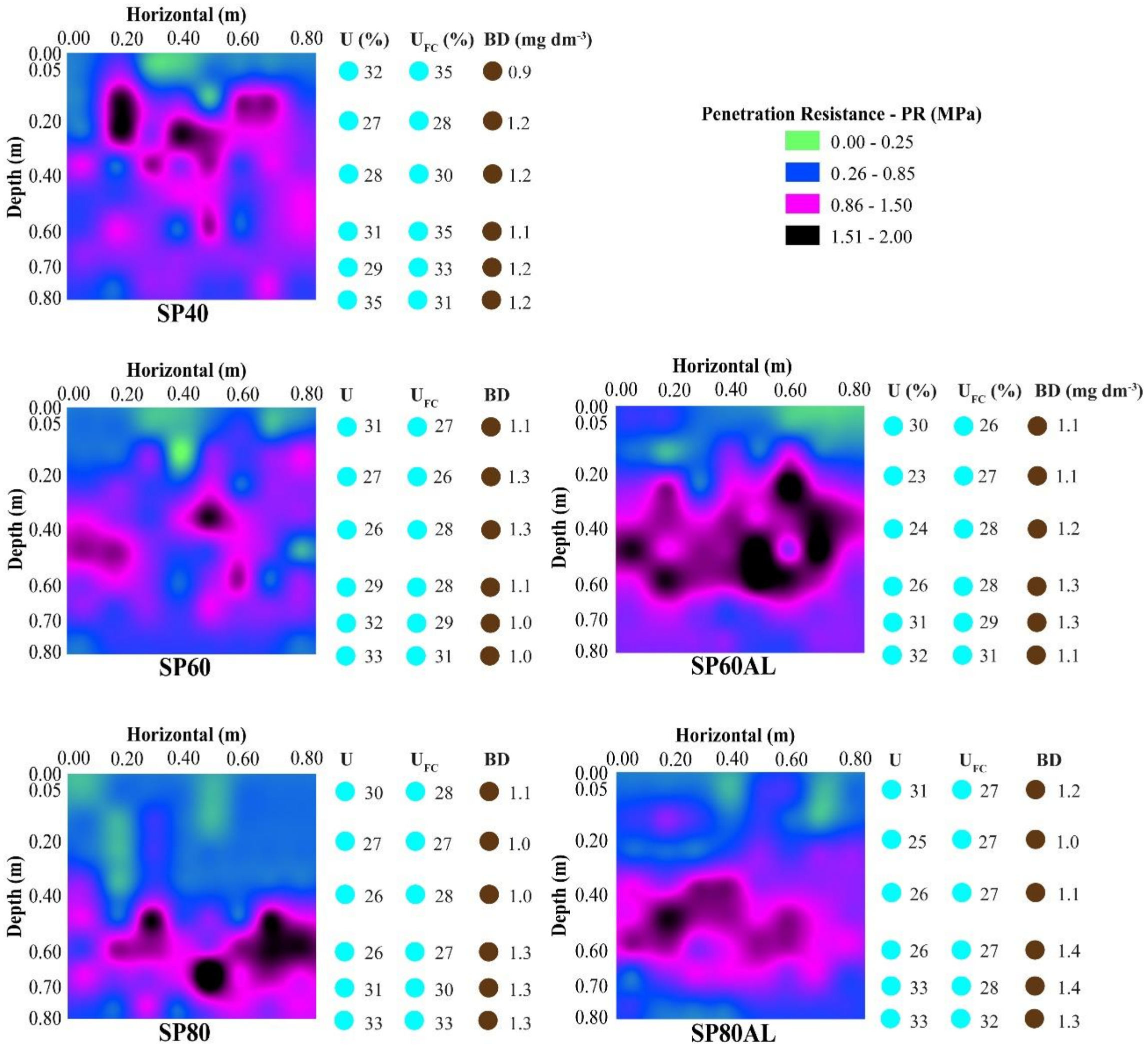


Figure 3. Spatial variability mapping of soil penetration resistance (in MPa) for different soil preparations: SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler. U: gravimetric water content (%); U_{FC}: gravimetric water content at field capacity estimated at -10 kPa (%); BD: bulk density (g dm^{-3}).

According to Franco et al. (2022), PR represents the mechanical force that the soil exerts against root movement or agricultural implements. The proportion of roots that penetrate the soil decreases as the resistance to penetration increases (Martino; Shaykewich, 1994). PR is influenced by cohesive forces and friction between soil particles, and the movement of these particles is necessary for root growth (Marshall et al., 1996; Silva et al., 2019).

Strategies involving deep tillage of the furrow reduced PR in the 0.10 to 0.25 m layer, resulting in a 29.77% decrease in soil bulk density (BD) compared to traditional tillage preparation. PR is a physical property that significantly varies with depth and depends on soil characteristics and the type of mechanization employed (Silva et al., 2019; Franco et al., 2022). In Figure 3, SP60 demonstrated lower PR variability and lower values along the soil profile, indicated by lighter colors, indicating minimal limitations to root growth, as confirmed by Figure 4. Conversely, SP60AL showed significant restrictions on root development, as evident in Figure 4. These limitations were observed in areas represented by darker colors in the PR map (Figure 3). For the SP60AL strategy, which included additional liming, PR ranged from 0.25 to 0.85 MPa within the first 0.20 m depth, followed by values between 0.86 and 2.00 MPa up to 0.70 m depth and a gradual increase in BD (Figure 3).

The result referring to the SP60AL showing more excellent resistance to penetration than the SP60 was not expected, given the improvements presented by the limestone, mainly in the beneficial alteration of the structural physical quality of Cambisols as extolled by Silva et al. (2016a). However, five years after the initial preparation and practice of additional liming, it is noted that its effects did not last over time. Nevertheless, Barbosa, studying this same experimental area, found expressive results associated with additional liming at the end of the second coffee cycle. Our results suggest that the extra amount of liming in the subsoil was not efficient in prolonging its effects over time, as the Ca^{2+} was already absorbed by the plants, mainly during the initial phase of coffee cultivation under rainfed conditions, as also highlighted by Barbosa et al. (2020).

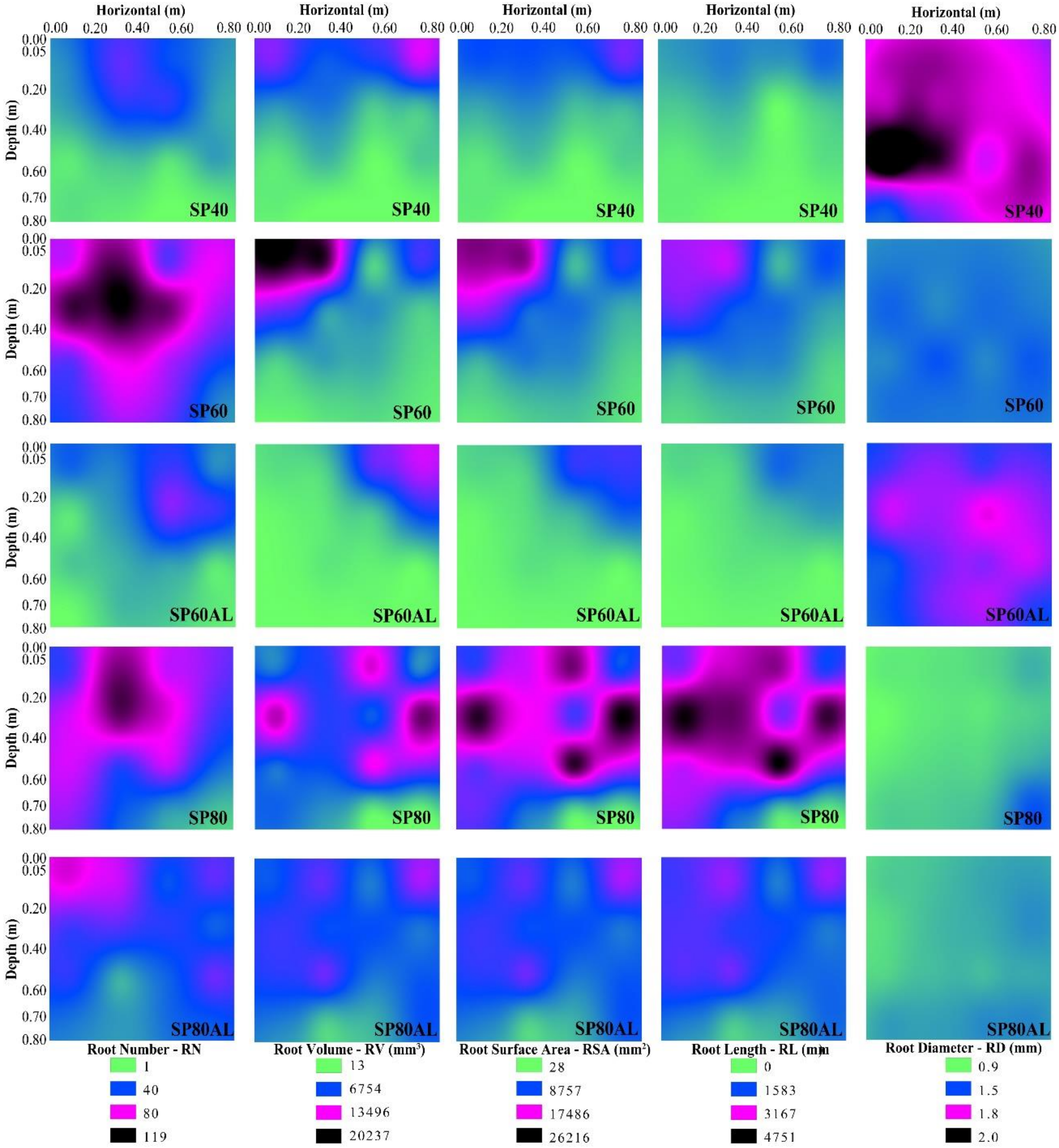


Figure 4. Spatial variability mapping of the coffee root system for different soil preparations: SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler.

The reduction in root growth due to increased soil resistance to penetration can vary among plant species (Martino; Shaykewich, 1994). A value of 2.0 MPa is generally considered limiting for most crops, based on moisture assessment at field capacity (Saffari et al., 2021). However, studies conducted in the Cerrado region, without irrigation, have shown that PR values between 1.26 and 4.0 MPa are considered limiting for coffee cultivation (Kobayashi et al., 2008; Silva et al., 2009). Furthermore, in Neossolo Flúvico Tb eutrófico, 2.5 MPa have been identified as a limiting factor for coffee plant growth (Souza et al., 2017).

Lima et al. (2010) used a reference PR value of 2.5 MPa for coffee intercropped with pasture in Cambisol soil close to the area of the present study. However, these authors noted that this soil's PR variation was lower than Oxisols and Argisols. Sene et al. (1985) mentioned that 2.5 MPa represents the critical force for clayey soils in their study on soil structure and texture in maize yield with subsoiling. However, all these studies calculated the critical PR values relative to field capacity, indicating that this value is specific to each soil type.

Based on the findings in figure 3, a PR value of 2 MPa can be considered limiting for the evaluated Cambisol, given the proximity of moisture levels between the collected samples (U %) and field capacity (U_{FC} %). When comparing the results of PR and BD (Figure 3) with the root system evaluation (Figure 4), limitations in the analyzed root variables occur in layers where PR is approximately 2 MPa and BD is equal to or greater than 1.2 mg dm^{-3}.

3.2. Growth and distribution of the root system

According to Carducci et al. (2014), soil structure significantly impacts root development, and root growth, in turn, affects soil structure. In the evaluated Cambisol, SP40, a traditional soil preparation used in coffee cultivation in Minas Gerais (Matielo et al., 2015), resulted in lower contributions to root number (NR), root volume (RV), and root surface area (RSA), while promoting thicker roots (1.8 < Ø < 2 mm) at the expense of finer roots responsible for absorption. Similarly, SP60AL showed considerable reductions in these variables and thicker roots compared to deep tillage with a subsoiler (SP80) and additional liming (SP80AL). These findings align with the higher PR values observed in the profiles of

SP40 and SP60AL (Figure 3), which negatively influenced root development. Previous studies conducted in the same experimental area, such as Barbosa et al. (2020), reported lower aeration, water availability, and structural physical quality due to higher soil density in SP40 preparation. Additionally, lower macroporosity and permeability were observed at the depth influenced by the furrower (0.40 m), as Silva et al. (2021) noted.

SP60 and SP80 exhibited superior root development up to a depth of 0.40 m, as depicted in figure 4. These soil preparations also demonstrated higher root numbers (RN) in the center of the planting furrow. Compared to SP40M, SP60, and SP80, they had lower calcium concentrations ($Ca \leq 0.55\%$ vs. $Ca \leq 1.10\%$), as shown in figure 3 of the supplementary material. Das et al. (2021) have reported that roots can mitigate soil limestone's effects. Therefore, the findings from previous research support the results in figure 4, where SP60 and SP80 had the highest root numbers ($NR \leq 119$), while SP40 had $NR \leq 40$. Notably, only SP60 was most effective in maintaining a mean geometric diameter (MGD) > 3 mm (Supplementary Material Figure 2A). All treatments exhibited high soil aggregate stability index (IAS) values above 80% (Supplementary Material Figure 2B). This condition suggests that the implemented soil preparations, regardless of the agricultural implementation used, demonstrated low degradation potential after five years of cultivation.

SP80 resulted in thinner roots (0.9 - 1.5 mm), essential for water and nutrient absorption (Carducci et al., 2015). Silva et al. (2021) highlighted that, 18 months after planting in the same coffee area, this specific preparation led to improvements in the hydraulic properties and porosity of the Cambisol, mainly when the soil homogenizer and subsoiler were used together, promoting the presence of macropores and mesopores up to a depth of 0.50 m.

According to Carducci et al. (2015), based on the work of Motta et al. (2006), roots with a diameter between 1 and 3 mm are considered medium-sized and have a supportive function but are less efficient in water absorption. In the present study, the most prominent root diameter observed was 2 mm, which differs from the findings of Carducci et al. (2015) in a more weathered soil profile (Oxisol), where medium and thick roots (Ø > 3 mm) were found. This difference can be attributed to the lower pedogenesis of Cambisols, resulting in a smaller network of pores than Oxisols. Additionally, root system characteristics may vary depending on plant age, root diameter, soil texture, and structure (Lynch, 1995).

Carducci et al. (2015) and Silva et al. (2016b) address that soil management with machinery at up to 0.60 m and adding gypsum on the surface promoted good root development of Arabica coffee in an Oxisol at three years of age. However, the results of the present study show that, for the evaluated Cambisol, the deep preparations with additional liming (SP60AL and SP80AL) showed a significant reduction in root development compared to the same practices without limestone (SP60 and SP80). It was also noted that the additional liming did not affect the aggregation variables (Supplementary Material Figure 2) and did not show pronounced effects concerning the distribution of calcium and magnesium along the soil profile (Supplementary Material Figure 3) for five years after the planting.

However, Barbosa et al. (2020) highlighted the efficiency of subsoiling with additional liming in improving aeration and water availability and reducing the density of this same Cambisol evaluated after two years of cultivation. However, our results, as also observed for PR, indicate that, after five years, this strategy related to the additional liming did not promote the best root development (Figure 4). Blumenschein et al. (2019), studying poorly drained and extremely acidic clayey soils in the USA's Midwest under corn and soybeans cultivation, address that the best effects of subsoil liming are obtained one year after application. On the other hand, Li et al. (2019) comprehensively analyzed multiple globally published studies from 1980 onwards, determining that the most suitable period for liming related to its duration is three years. This temporal efficacy is intricately associated with dynamic alterations in environmental conditions. These research works may explain the positive results found by Barbosa et al. (2020) when relating attributes of the physical quality of the soil concerning the practice of additional liming.

SP40 and SP60AL exhibited higher root concentrations up to a depth of 0.40 m (Figure 4). In contrast, the other preparations showed more uniform root distribution in deeper layers (0.60 to 0.80 m), particularly in the case of SP80AL (Figure 4), potentially due to the higher soil density observed in this layer (Figure 3). Beyond 0.50 m depth, both SP60 and SP80 significantly reduced root variables, particularly in RL for SP60 (Figure 4). These findings suggest soil compression near the equipment's maximum working depth (Silva et al., 2021). Negatively impacting soil structure can occur if soil type, equipment, depth, and operating speed during preparation are not considered, as Ahmadi (2018) emphasized. Additionally, Nunes et al. (2021) state that soil compaction can lead to lateral root growth, which is supported by the observed trends in RV, RSA, and RL across all soil preparations (Figure 4).

Partelli et al. (2020) found greater volume and surface area of Arabica coffee roots in the surface layers of an Oxisol, with a reduction at greater depths. However, despite their dense matrix, Serafim et al. (2013c) observed good root growth at depth in Cambisol. These authors underscore the importance of adopting deep soil management (preparation at 0.60 m) in conjunction with soil conservation practices, such as maintaining cultivated rows, as was also implemented in the present study's experimental setting.

3.3. Spatiotemporal variation of soil water content

During the study period from October 2019 to March 2021, rainfall distribution (Figure 5A) impacted the water content variability in the Cambisol profile, as shown by the map of the monitoring of moisture over time (MMOT) (Figure 5B). A drier period was observed between April 2020 and September 2020, while two wetter seasons occurred between October 2019 and March 2020 and between October 2020 and March 2021. The total precipitation during the study period was 2718.2 mm, close to the standard climatological average for the region of 2705.6 mm. In the wet period, 1547 mm of rainfall was recorded in 2020 and 1126 mm in 2021, while during the dry period, only 45 mm of rain occurred over 183 days (Figure 5A). The period with the highest water deficit was between June and July 2020, with precipitation ≤ 1 mm (Figure 5A).

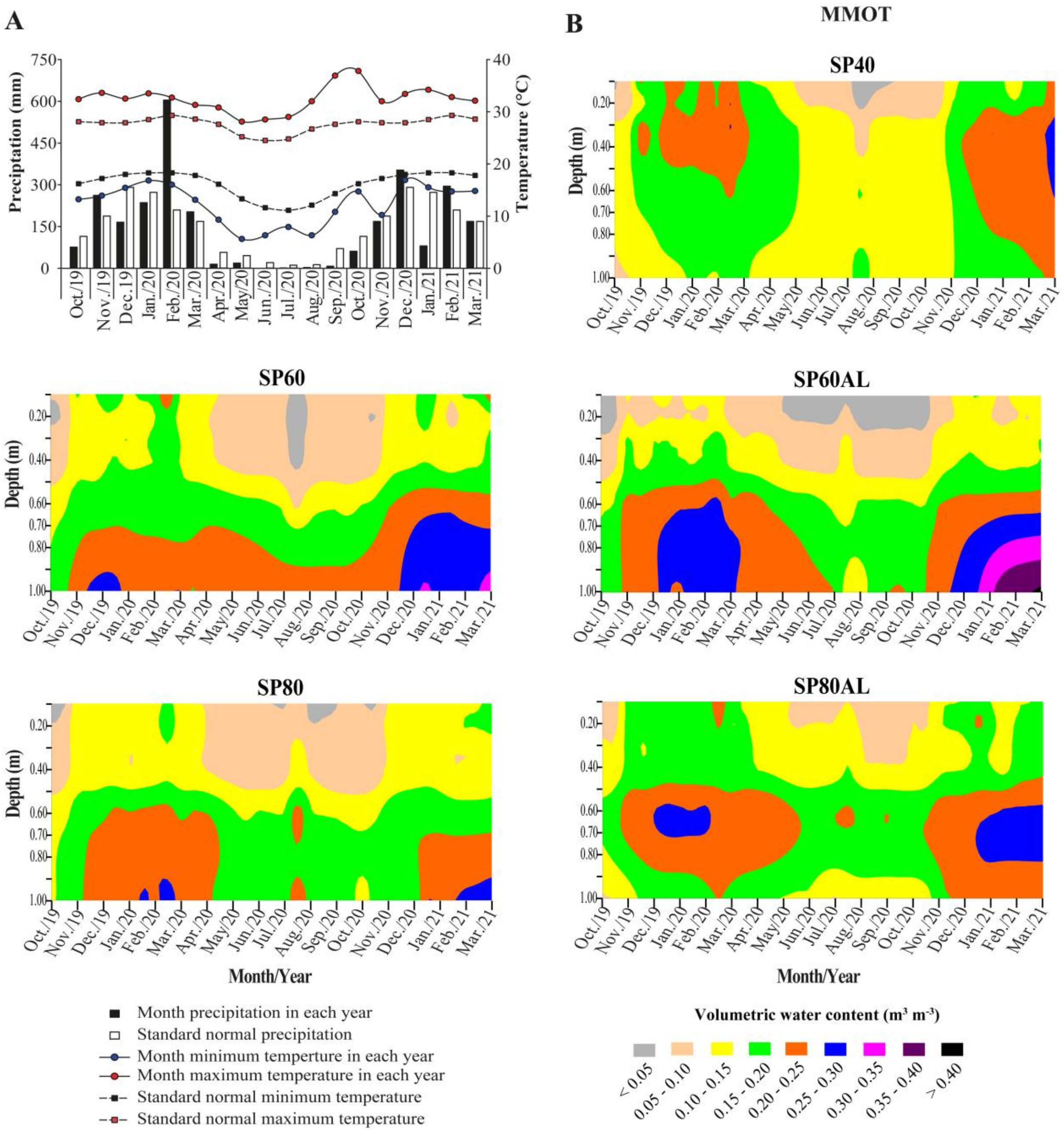


Figure 5. Monthly precipitation and temperature for 2019 to 2021 and climatological standard normals from the period 1981 - 2010; and spatial and temporal variability maps of the soil water content monitoring over time for different soil preparations: SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler.

Figure 5A indicates that water availability may be related to the water demand of coffee plants. According to Bernardo (2002), a coffee plant typically requires 800 to 1200 mm of water per production cycle without losing productivity. In figure 5, it can be observed that the 4th cycle (October 2019 to August 2020) had a rainfall of 1585 mm, while part of the 5th cycle (September 2020 to March 2021) recorded 1133 mm, indicating favorable conditions for the cultivation of Arabica coffee (Thomaziello et al., 2000).

The data show a range of 12 to 32º C in terms of temperature, with the maximum limit (22.5° C) being exceeded by 42.22%. However, Thomaziello et al. (2000) indicate that arabica coffee tends to have better development in regions where the average annual temperature varies between 18 and 22º C. Assad et al. (2001) also note that the ideal yearly temperature for the coffee plant should be between 18 and 23° C.

The average annual temperature for 2020 (4th cycle) was 22° C, as shown in the data (Figure 5A). This temperature falls within the range considered suitable for coffee cultivation, considering that this crop has a well-defined phenological cycle. High temperatures can hinder flowering and result in reduced fruiting, which affects production, especially during periods of prolonged drought (Camargo, 1995).

Alvarenga et al. (2018) analyzed the Rio Grande watershed region in Minas Gerais, Brazil, the same region as this study. These authors observed that from 1961 to 1990, the negative water balance occurred between April and July. However, since 2006, the dry period has been extended, with the water deficit occurring from March to August. These changes in hydrological cycles highlight the need for better management of water resources, especially to anticipate problems arising from soil drought, which can significantly impact the agricultural sector.

According to figure 5B, SP40 exhibits less variability in water content across the soil profile than deep tillage strategies. This condition results in higher water content up to a depth of 0.40 m and homogeneity throughout the entire soil profile (up to 1 m depth). This condition can be attributed to the lower volume of roots present for water absorption in the furrower (Figure 4). The map in figure 5B shows variation with lighter colors indicating higher water content for the traditional preparation, with alternation between wet periods (from October/2019 to March/2020 and from October/2020 to March/2021: $0.15 \leq \theta \leq 0.25$ m^3 m^{-3}) and a dry period (from April to September/2020: $0.05 \leq \theta \leq 0.20$ m^3 m^{-3}).

On the other hand, SP60 and SP80 exhibited lower values of stored water content in wet periods up to a depth of 0.40 m compared to SP40. These results agree with the observations in figure 4, where the deep preparations of the planting furrow without additional liming showed better root development, characterized by a more significant number, volume, and surface area of roots and a larger diameter of absorptive roots at that depth. These findings support the results of Silva et al. (2015), who observed a reduction in water content in an Oxisol profile under coffee cultivation and related these results to the extensive root system that occupied large volumes of the soil. Therefore, soil preparation influences the water storage capacity in the soil profile and, consequently, its release and absorption by the roots, especially in coffee crops.

The research conducted by Jackson et al. (2000) emphasizes the influence of soil moisture and root water absorption on water fluxes in the soil. Pimentel (2004) also acknowledges the relationship between the amount of water plants absorb and the volume of soil occupied by roots, mainly when water is available. However, previous studies have not adequately addressed the interaction between soil type, physical properties, root system architecture, and their combined effects on agricultural management. Therefore, there is still a gap in our understanding of this aspect, which is crucial for a comprehensive understanding of the subject.

Regarding deep tillage strategies (SP60 and SP80) and tillage with additional liming (SP60AL and SP80AL), they exhibited more significant variability in water content across the soil profile compared to seasonal variation, especially for SP60 (Figure 5B). Generally, water content values were lower ($0.05 \leq \theta \leq 0.20$ m^3 m^{-3}) in the superficial layers (0-0.40 m) and increased with depth (> 0.40 - 1 m), reaching up to 0.30 m^3 m^{-3} during the rainy season and decreasing to 0.15 m^3 m^{-3} during the driest period. Only SP60 and SP60AL showed water content above 0.30 m^3 m^{-3} during the 2021 rainy season but at depths greater than 0.80 m. However, this condition does not necessarily indicate better water absorption by the roots, as at the same depth and for the same preparations, there is a high concentration of Al (approximately 11.32%) (Figure 3 of the supplementary material), which resulted in a reduction in root variables, particularly RSA ≤ 28 mm^2 (Figure 4).

Figure 5B suggests that SP60 maintains a relatively constant water volume throughout the year, starting from a depth of 0.50 m, indicating less seasonal variation in water content. Soil preparations with additional liming increase the water content starting from 0.60 m, particularly for SP80AL, which maintains a water content between 0.15 and 0.20 m^3 m^{-3} up to 0.40 m during the wettest periods. During the dry period, the subsoiler with additional liming is the only one with water content above 0.05 m^3 m^{-3} in the top 0.10 m of soil. However, SP80AL also shows increased resistance to penetration from 0.10 m (Figure 3) and a lower number of roots in this region (Figure 4), which may hinder water absorption and promote its accumulation, as indicated in figure 5B.

SP40 exhibited a water content below the plant's availability (< 0.25 m^3 m^{-3}) throughout the dry period in the soil profile (Figure 5B), which hampers the development of coffee plants, especially during flowering and fruit expansion phases, leading to reduced productivity and grain quality (Oliveira et al., 2012). Available water (0.25 - 0.35 m^3 m^{-3}) was concentrated in layers below 0.35 - 0.65 m for SP40 and below 0.60 m for the other deep tillage strategies. In the surface layers, evapotranspiration influences water content more due to sunlight exposure and drainage. For depths greater than 0.60 m, the drying effect due to evapotranspiration becomes more pronounced, resulting in water retention in smaller pores during the dry period, while water passing through larger pores contributes to the water table (Silva et al., 2015).

Most of the root system is concentrated in the surface layer (0 - 0.20 m) (Figure 4), contributing to water absorption. This region is the driest in the soil profile (Jackson et al., 2000; Pimentel, 2004; Silva et al., 2015). As we move deeper into the soil, evaporation has a lesser effect, and water content is more influenced by drainage. This condition was observed mainly for SP60AL below 0.80 m during high precipitation and for SP60 in root absorption. In both cases, a larger volume of roots is expected to be associated with drier soil and vice versa. Arruda et al. (2000) suggest that water consumption by coffee plants ceases when 113 mm of water is depleted along the 0-1 m soil profile. On the other hand, Camargo (1985) proposes a value of 150 mm/year as a water deficiency threshold and a limiting factor for coffee cultivation. Therefore, our data indicating an average annual precipitation of 139 mm for 2020 (Figure 5A) suggest a water deficit for coffee plants during the evaluated period.

Deep furrow preparations with added liming showed significant potential to increase water content in deep layers of the soil profile (0.60 - 0.70 m) during the dry season (Figure 5B). This water reserve can be utilized by plants since, regardless of the evaluated root variable, SP80AL mechanically developed up to a depth of 0.80 m (Figure 4). Carducci et al. (2015) indicate that coffee roots can reach depths greater than 1 m, and at the same depth, there is improved water availability to plants during the rainy season for SP80, SP60, and SP60AL (Figure 5B).

3.4. The activity of the plant's antioxidant system

Comparing different soil preparation during the dry and wet periods, variations in antioxidant enzyme activity (APX, CAT, and SOD) were observed (Figure 8). In the dry period, SP60 showed higher activity for APX, CAT, and SOD than other soil preparations and SP40. On the other hand, SP80 and SP80AL exhibited lower activity for all antioxidant enzymes, although they did not statistically differ from traditional preparation. During the dry period, SP60 and SP80AL reduced hydrogen peroxide, lipid peroxidation, and protein levels in coffee leaves compared to SP60AL and SP80. In the wet period, SP60AL, which involved soil preparation up to 0.60 m with additional liming, showed higher APX enzyme activity and reduced hydrogen peroxide than other soil preparations and the traditional preparer (Figure 8).

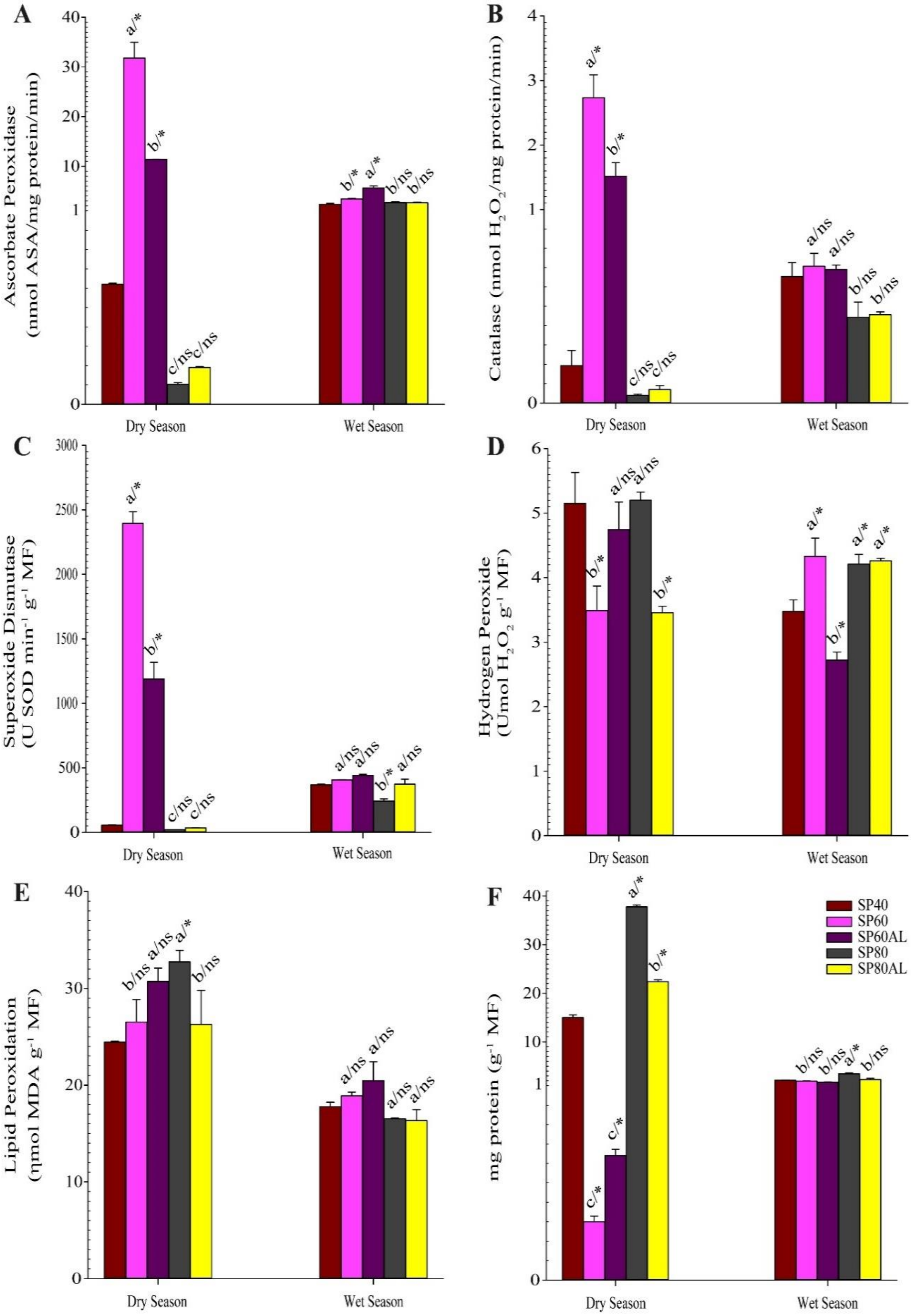


Figure 6. Antioxidant enzymes: Ascorbate Peroxidase – APX (A); Catalase – CAT (B); Superoxide Dismutase – SOD (C); Hydrogen Peroxide (D), Lipid Peroxidation (E) and Total Protein (F) for different soil preparations: SP40: planting furrow at 0.40 m with conventional

fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler. Bars followed by the same lowercase letters do not differ by the Skott-Knott test ($p < 0.05$) and compare the preparations (SP60; SP60AL; SP80, and SP80AL) with each other. Bars followed by an * differ from each other by Dunnett's test ($p < 0.05$), ns: not significant by the F test ($p < 0.05$) when compared to the reference preparation (SP40).

SOD is a key enzyme that plays a crucial role in plant tolerance to oxidative stress by removing the superoxide radical (O_2^-) and controlling reactive oxygen species (ROS). Its reaction produces hydrogen peroxide (H_2O_2) and O_2^-, converting O_2^- to H_2O_2 (Mittler, 2002; Verma, Dubey 2003). According to León et al. (2002), SOD is involved in plant defense mechanisms as it prevents the formation of the hydroxyl radical $(OH)^-$. However, H_2O_2 is toxic to the cell and needs to be reduced by CAT and APX (Willekens et al., 1995; Asada, 1999). CAT, found in peroxisomes, removes H_2O_2 when it is present in high concentrations in the cell (Mittler, 2002). On the other hand, APX is crucial in the ascorbate/glutathione cycle, reducing H_2O_2 when it is in low concentrations in the cell (Asada; Takahashi, 1987). These enzymes are essential in lowering ROS, especially under water deficit stress conditions, as this scenario rapidly leads to the generation of ROS such as O_2^-, OH^-, and H_2O_2, causing severe toxicity and imbalance between ROS and the antioxidant defense system (Campos et al., 2019; Cherono et al., 2021).

The best adaptation and performance of coffee plants, resulting in higher enzymatic activity, were observed when the planting furrow was opened up to 0.60 m deep. However, this was not the case when the furrow was opened up to 0.80 m deep under adverse drought conditions (Figure 8A, B, and C). The improved physical properties of the soil and root system development contributed to this better performance with SP60. The higher enzymatic activity in SP60 aligns with the discussed moisture maps. SP60 maintained a moisture range of 0.05 - 0.10 m^3 m^{-3} up to 0.60 m depth throughout the dry period, whereas SP80AL had a 0.10 - 0.20 m^3 m^{-3} range (Figure 6B). This condition correlates with the findings of Campos et al. (2019) and Cherono et al. (2021), who studied oxidative stress through enzymatic activities in coffee leaves (*Coffea arábica* L.) and noted that increased SOD, CAT, and APX activities are beneficial under water stress as these enzymes detoxify ROS. Thus, the higher enzymatic activity observed in SP60 can be attributed to its lower water storage range of up to 0.60 m, a condition not marked in SP80AL.

Under adverse drought conditions, both SP60 and SP80AL, with high and low enzymatic activity, reduced hydrogen peroxide and lipid peroxidation (Figure 8D and E). Only SP60AL showed increased APX activity during the wet period and reduced hydrogen peroxide (Figures 8A and D). These results are significant and indicate the coffee plant's stress condition, particularly with SP60, as an excess of ROS in the cell can damage cellular structures and biomolecules. Evaluating plant stress based on antioxidant activity is associated with combating ROS (Rejeb et al., 2014).

Hydrogen peroxide is highly toxic to cells (Willekens et al., 1995; Asada, 1999) and, if left uncontrolled, can induce stomatal closure, especially under water stress conditions (Deuner et al., 2011). Stomatal closure is the primary strategy employed by coffee plants to minimize water loss through transpiration (Barros et al., 1997) or during periods of low water availability (DaMatta et al., 2000). Increased lipid peroxidation indicates cell membrane damage and ion leakage, affecting membrane functionality (Farooq et al., 2009). Cherono et al. (2021) support this by highlighting that reduced lipid peroxidation attenuates cellular membrane integrity and stability damage, enhancing plant resistance under water deficit conditions.

In adverse conditions, especially during the dry period, higher activity of the enzymes SOD, CAT, and APX is beneficial. Based on the data from Figure 8, the planting furrow opened up to 0.60 m without additional liming was the most advantageous preparation for coffee plant establishment in the evaluated field conditions. It was also the most cost-effective for producers, as it involved using only one agricultural equipment (Big Mix) and was linked to conventional fertility management, compared to two agricultural implements (Mig Mix + Dreno) and additional additional liming (200 g) in the SP80AL preparer. However, it is worth noting that SP80AL also improved water content (Figure 5). Still, it was not the most cost-effective option since it provided similar results in reducing H_2O_2 and cell damage compared to SP60.

The condition imposed by SP60 aligns with Figure 3 from the supplementary material, as this soil preparation showed lower Mg (%) concentrations than SP40 and SP80, despite receiving the same initial soil fertility levels for this specific element. However, the preparation up to 0.60 m without additional chemical correction exhibited higher NR > 119 throughout the soil profile (Figure 4), attributed to lower penetration resistance (Figure 3), which likely facilitated more excellent nutrient absorption, favoring metabolic processes (Guarçoni; Sobreira, 2017). These findings justify the results observed in Figure 8.

Faiz et al. (2022) state magnesium enhances antioxidant enzyme activity and detoxifies ROS. However, SP80AL also reduced hydrogen peroxide and lipid peroxidation despite having lower enzymatic activity than SP60AL, indicating that the soil preparation followed by drainage and additional liming benefitted the coffee plants in dry and wet periods. However, specific to calcium, Figure 3 from the supplementary material shows that SP80AL has lower levels than SP60AL. This result suggests that the additional limestone applied between 0.20 to 0.60 m depth, incorporated through rotary hoeing followed by subsurface plowing (SP80AL), was absorbed by the plants, and activated alternative metabolic pathways, favoring aboveground growth since this preparation did not exhibit root growth throughout the Cambisol profile like SP60 (Figure 4). Garcia et al. (2019) highlight that ROS can be produced in chloroplasts, mitochondria, and peroxisomes, and their production rate varies with the plant's physiological state. ROS act as intercellular signals at low concentrations, regulating various physiological processes in response to environmental stimuli (Baxter et al., 2014). Therefore, these results may be associated with the coffee plant's genetic potential, as it possesses physiological and biochemical mechanisms that enable growth and development. Thus, the coffee plants adapted better by preparing up to 0.60 m in naturally dense Cambisols.

The unexpected reduction in proteins and lipid oxidation indicates cellular damage caused by ROS (Deuner et al., 2011). According to DaMatta et al. (2018), coffee plants may suffer severe damage to cellular structures and proteins involved in physiological metabolism under extreme drought conditions. This scenario justifies the reduced protein levels during low precipitation for SP60, SP60AL, and SP80AL in the dry period but increased protein levels for SP80 in both dry and wet periods (Figure 8F). However, the protein reduction in SP60 was not detrimental; on the contrary, it can be justified by the high activity of SOD, CAT, and APX, which combat oxidative stress in plant cells and promote more excellent antioxidant protection. Additionally, the positive contributions highlighted in previous sections, such as soil structural physical quality, soil penetration resistance, and root system, support the outcome for SP60. These benefits were not observed for SP60AL and SP80. The soil preparation itself can explain this scenario and, as Sousa et al. (2022) suggested, the plants' acclimation, as they can adjust to changes according to their environment.

4. Conclusions

Compared to traditional soil preparation, the deep opening of planting furrows has shown promise in mitigating water stress caused by drought in naturally dense Cambisol.

Opening and homogenizing the soil up to 0.60 m (using the Big Mix implement) resulted in lower resistance to penetration in the subsurface layer (0.10 - 0.25 m), allowing for significant root growth up to 0.40 m. However, this preparation led to lower water storage during the dry period, triggering higher enzymatic activity of the antioxidant system, significantly reducing hydrogen peroxide and lipid peroxidation. On the other hand, soil preparation with a subsoiler up to 0.80 m to open the planting furrow, combined with additional liming up to 0.60 m, promoted the better distribution of calcium and magnesium in the soil profile due to lower aluminum levels. This preparation strategy improved deep water storage in the Cambisol during the dry period, resulting in lower hydrogen peroxide and lipid peroxidation levels, despite the lower enzymatic activity of the antioxidant system. However, it was not the most cost-effective option for producers since SP60 provided similar results, indicating greater drought tolerance due to its improvements in physical properties.

The development of spatial variation maps for soil profile variables, including resistance to soil penetration, root system growth, water content, and nutrient content, revealed evidence of compaction at the bottom of the planting furrow due to machinery entry outside the friability zone during preparation. The root expansion reduction occurred at the equipment's expected working depth and persisted even after five years. This condition emphasizes the significance of meticulous planning and execution of initial soil preparation for perennial crops, as profound root growth is vital for mitigating water stress.

5. Referências

Ahmadi, I., 2018. A draught force estimator for disc harrow using the laws of classical soil mechanics. Biosyst. Eng. 171, 52–62. https://doi.org/10.1016/j.biosystemseng.2018.04.008.

Ajayi, A.E., Dias Junior, M.D.S., Curi, N., Araujo Junior, C.F., Aladenola, O.O., Teixeira Souza, T.T., Inda Junior, A.V., 2009. Comparison of estimation methods of soil strength in five soils. Rev. Bras. Cienc. Solo. 33, 487–495. https://doi.org/10.1590/S0100-06832009000300002.

Alvarenga, L.A., de Mello, C.R., Colombo, A., Chou, S.C., Cuartas, L.A., Viola, M.R., 2018. Impacts of climate change on the hydrology of a small brazilian headwater catchment using the Distributed Hydrology-Soil-Vegetation Model. Am. J. Clim. Change. 7, 355. https://doi.org/10.4236/ajcc.2018.72021.

Arruda, F.B., Iaffe, Â., Weill, M.D.A.M., Sakai, E., Calheiros, R.D.O., 2000. Resultados do consumo de água e do coeficiente de cultura do cafeeiro a partir do controle da umidade do solo em Pindorama. Anais do Simpósio De Pesquisas Dos Cafés Do Brasil, 1, Poços de Caldas. p.775–778. http://www.sbicafe.ufv.br/handle/123456789/905.

Asada, K., 1999. The water-water cycle in chloroplasts: scavenging of active oxygens and dissipation of excess photons. Annu. Rev. Plant Biol. 50, 601–639. https://doi.org/10.1146/annurev.arplant.50.1.601.

Asada, K., Takahashi, M. Production and Scavenging of Active Oxygenin Photosynthesis; Kyle, D.J., Osmond, C.B., Arntzen, C.J., Eds.; Elsevier: Amsterdam, The Netherlands, 1987; pp. 227–287.

Assad, E.D., Evangelista, B., Silva, F.D., Cunha, S.D., Alves, E.R., Lopes, T.D.S., Pinto, H..S., Zullo Junior, J., 2001. Zoneamento agroclimático para a cultura do café (*Coffea arabica* L.) no Estado de Goiás e sudoeste do Estado da Bahia. Rev. Bras. de Meteorol. 9, 510–518.

Barbosa, S.M., Oliveira, G.C.de., Silva, B.M., Benevenute, P.A.N., Silva, R.F.DA., Curi, N., Moretti, B.DA.S., Silva, S.H.G., Norton, L.D., Pereira, V.M., 2020. Deep furrow and additional liming for coffee cultivation under first year in a naturaly dense inceptisol. Geoderma. 357, 113934. https://doi.org/10.1016/j.geoderma.2019.113934.

Barros, R.S., Mota, J.W., DaMatta, F.M.; Maestri, M., 1997. Decline of vegetative growth in *Coffea arabica* L. in relation to leaf temperature, water potential and stomatal conductance. Field Crops Res. 54, 65–72. https://doi.org/10.1016/S0378-4290(97)00045-2.

Baxter, A., Mittler, R., Suzuki, N., 2014. ROS as key players in plant stress signalling. J. Exp. Bot. 65, 1229-1240. https://doi.org/10.1093/jxb/ert375.

Bazame, H.C., Molin, J.P., Althoff, D., Martello, M., 2021. Detection, classification, and mapping of coffee fruits during harvest with computer vision. Comput. Electron. Agric. 183, 106066. https://doi.org/10.1016/j.compag.2021.106066.

Bernardo, S. Manual de Irrigação. UFV: Viçosa - MG. 6 ed., 2002. 656p.

Biemelt, S., Keetman, U., Albrecht, G., 1998. Re-Aeration following hypoxia or anoxia leads to activation of the antioxidative defense system in roots of wheat seedlings. Plant Physiol. 116, 651–658. https://doi.org/10.1104/pp.116.2.651.

Blumenschein, T.G., Nelson, K.A., Motavalli, P.P., 2019. Changes in subsoil acidity with a new deep vertical lime placement practice for conservation tillage systems J. Soil Water Conserv. 74, 426–438. https://doi.org/10.2489/jswc.74.5.426.

Bortolanza, D.R., Klein, V.A., 2016. Soil chemical and physical properties on an Inceptisol after liming (surface and incorporated) associated with gypsum application. Rev. Bras. Cienc. Solo. 40, 0150377. https://doi.org/10.1590/18069657rbcs20150377.

Bradford, M.M., 1976. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Anal. Biochem. 72, 248–254. https://doi.org/10.1016/0003-2697(76)90527-90523.

Camargo, A.P., 1985. O clima e a cafeicultura no Brasil. Revista Informe Agropecuário. Belo Horizonte, Minas Gerais. 11, pp.13–26.

Campos, C.N., Ávila, R.G., de Souza, K.R.D., Azevedo, L.M., Alves, J.D., 2019. Melatonin reduces oxidative stress and promotes drought tolerance in young *Coffea arabica* L. plants. Agric. Water Manag. 211, 37–47. https://doi.org/10.1016/j.agwat.2018.09.025.

Carducci, C.E., Oliveira, G.C., Curi, N., Heck, R.J., Rossoni, D.F.F., Carvalho, T.S.S.; Costa, L.L., 2015. Gypsum effects on the spatial distribution of coffee roots and the pores system in oxidic Brazilian Latosol. Soil Tillage Res. 145, 171–180. https://doi.org/10.1016/j.still.2014.09.015.

Carducci, C.E., Oliveira, G.C., Lima, J.M., Rossoni, D.F., Costa, A.L., Oliveira, L.M., 2014. Distribuição espacial das raízes de cafeeiro e dos poros de dois Latossolos sob manejo conservacionista. Rev. Bras. de Eng. Agricola e Ambient. 18, 270–278. https://doi.org/10.1590/S1415-43662014000300005.

Cherono, S., Ntini, C., Wassie, M., Mollah, M.D., Belal, M.A., Ogutu, C., Han, Y., 2021. Exogenous Application of Melatonin Improves Drought Tolerance in Coffee by Regulating Photosynthetic Efficiency and Oxidative Damage, Journal of the American Society for Horticultural Science J. Amer. Soc. Hort. Sci. 146, 24–32. https://doi.org/10.21273/JASHS04964-20.

Companhia Nacional de Abastecimento (Conab), 2022. Acompanhamento da safra brasileira, café, safra 2022 1º levantamento, janeiro de 2022, volume 9, número 1.

DaMatta, F.M., Avila, R.T., Cardoso, A.A., Martins, S.C.V., and Ramalho, J.C., 2018. Physiological and agronomic performance of the coffee crop in the context of climate change and global warming: a review. J. Agric. Food Chem. 66, 5264–5274. https://10.1021/acs.jafc.7b04537.

Damatta, F.M., Silveira, J.S.M., Ducatti, C., Loureiro, M.E., 2000. Eficiência do uso da água e tolerância à seca em *Coffea canephora*. In: SIMPÓSIO DE PESQUISA DOS CAFÉS DO BRASIL, 1., 2000, Brasília. Expanded Abstract. Brasília: EMBRAPA Café, 2000. p. 907-910

Das, G., Razakamanantsoa, A., Herrier, G., Saussaye, L., Lesueur, D., Deneele, D., 2021. Evaluation of the long-term effect of lime treatment on a silty soil embankment after seven years of atmospheric exposure: Mechanical, physicochemical, and microstructural studies. Eng. Geol. 281, 105986. https://doi.org/10.1016/j.enggeo.2020.105986.

de Sousa, G.F.; Silva, M.A.; de Morais, E.G.; Van Opbergen, G.A.Z.; Van Opbergen, G.G.A.Z.; de Oliveira, R.R.; Amaral, D.; Brown, P.; Chalfun-Junior, A.; Guilherme, L.R.G., 2022. Selenium enhances chilling stress tolerance in coffee species by modulating nutrient, carbohydrates, and amino acids content. Front. Plant Sci. 13, 1000430. https://doi.org/10.3389/fpls.2022.1000430.

Delta-T: User Manual for the Profile Probe type PR2 Profile Probe – SDI-12 version Delta-T Devices Ltd. https://delta-t.co.uk/pr2-profile-probe-sdi-12-version/ (accessed 08 August 2019).

Deuner, S., Alves, J. D., Zanandrea, I., Goulart, P.D.F.P., Silveira, N.M., Henrique, P.D. C., Mesquita, A.C., 2011. Stomatal behavior and components of the antioxidative system in coffee plants under water stress. Sci. Agric. 68, 77–85. https://doi.org/10.1590/S0103-90162011000100012.

Faiz, S., Yasin, N.A., Khan, W.U., Shah, A.A., Akram, W., Ahmad, A., Ali, A., Huma, N., Riaz, L., 2022. Role of magnesium oxide nanoparticles in the mitigation of lead-induced stress in Daucus carota: modulation in polyamines and antioxidant enzymes. Int. J. Phytoremediation. 24, 364–372. https://doi.org/10.1080/15226514.2021.1949263.

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D., Basra, S.M.A., 2009. Plant drought stress: effects, mechanisms and management. Sustain. Agric. pp.153–188. https://doi.org/10.1007/978-90-481-2666-8_12.

Franco, T.C., Ferraz, G.A., Carvalho, L.C., Silva, F.M., Alves, M.C., Marin, D.B., 2022. Spatial variability of soil physical properties in longitudinal profiles. An. Acad. Bras. Cienc. 94, 1–17. https://doi.org/10.1590/0001-3765202220200411.

Garcia, F.H.S., Matute, A.F.M., Silva, L.C., Santos, H.R.B., Botelho, D.S., Rodrigues, M., Barbosa, J.P.R.A.D., 2019. Análise fisiológica em mudas de cafeeiro com cercosporiose submetida a diferentes lâminas de irrigação. Summa Phytopathol., Botucatu. 45, 83-88, 2019. https://doi.org/10.1590/0100-5405/185711.

Giannopolitis, C.N., Ries, S.K., 1977. Superoxide dismutases: I. occurrence in higher plants. Plant Physiol. 59, 309-314. https://doi.org/10.1104/pp.59.2.309.

Grohmann, F., Conagin, A., 1960. Técnica para o estudo da estabilidade de agregados do solo. Bragantia, 19, 329-343. https://doi.org/10.1590/S0006-87051960000100022.

Guarçoni, A., Sobreira, F.M., 2017. Classical methods and calculation algorithms for determining lime requirements. Division 3 - Soil Use and Management. Rev. Bras. Ciênc. Solo. 41, e0160069. https://doi.org/10.1590/18069657rbcs20160069.

Guimarães, P.T.G., Garcia, A.W.R., Alvarez V.V.H., Prezotti, L.C., Viana, A.S., Miguel, A.E., Oliveira, J.D., 1999. Cafeeiro. CFSMG - Comissão de Fertilidade do Solo do Estado de

Minas Gerais. Recomendação para o uso de corretivos e fertilizantes em Minas Gerais, 5ª aproximação. Viçosa.

Havir, E.A., and McHale, N.A., 1987. Biochemical and developmental characterization of multiple forms of catalase in tobacco leaves. Plant Physiol. 84, 450–455. https://doi.org/10.1104/pp.84.2.450.

Havlicek, E., Mitchell, E.A., 2014. Soils supporting biodiversity. In: Interactions in Soil: Promoting Plant Growth. Springer, Dordrecht, pp. 27–58. https://doi.org/10.1007/978-94-017-8890-8_2.

Horta, I.M.F., Pereira, J.A.A, Marques, J.J., Carvalho, L.M.T., 2009. Levantamento de reconhecimento com apoio digital dos solos do município de Nazareno-MG. Ciência e Agrotecnologia. 33 p.1940–1947. https://doi.org/10.1590/S1413-70542009000700042.

Jackson, R.B., Sperry, J.S., Dawson, T.E., 2000. Root water uptake and transport: using physiological processes in global predictions. Trends Plant Sci. 5, 482–488. https://doi.org/10.1016/S1360-1385(00)01766-0.

Jawo, T.O., Kyereh, D., Lojka, B., 2022. The impact of climate change on coffee production of small farmers and their adaptation strategies: a review. Clim. Dev. 15, 93–109. https://doi.org/10.1080/17565529.2022.2057906.

Jorge, L.A.C., Silva, D.J.C.B., 2010. SAFIRA: Manual de utilização. São Carlos: Embrapa CPDIA, 29p. Available in: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/884593/safira-manual-de-utilizacao.

Kobayashi, E.S., Sakai, E., Silva, E.A.D., Arruda, F.B., Silveira, J.M.D.C., Souza, P.S. D., Pires, R.C.D.M., 2008. Seasonal changes in coffee leaf water potential in Mococa, São Paulo State, Brazil. Bragantia, 67, 421–428. https://doi.org/10.1590/S0006-87052008000200018.

Lee, S., Wolberg, G., Shin, S.Y., 1997. Scattered data interpolation with multilevel B-splines. IEEE Trans. Vis. Comput. Graph. 3, 228–244. https://doi.org/10.1109/2945.620490.

León, A.M., Palma, J.M., Corpas, F.J., Gómez, M., Romero-Puertas, M.C., Chatterjee, D., Mateos, R.M., del Río, L.A., Sandalio, L.M., 2002. Antioxidative enzymes in cultivars of pepper plants with different sensitivity to cadmium. Plant Physiol. Biochem. 40, 813-820. https://doi.org/10.1016/S0981-9428(02)01444-4.

Li, Y., Cui, S., Chang, S. X., Zhang, Q., 2019. Liming effects on soil pH and crop yield depend on lime material type, application method and rate, and crop species: a global meta-analysis. Journal of Soils and Sediments. 19, 1393-1406. https://doi.org/10.1007/s11368-018-2120-2

Lima, V.M.P., Magalhães, C.A.D.S., Oliveira, G.C., Lima, J.M.D., 2010. Structural quality of soils cultivated with coffee and pasture in an environmental protection area. Rev. Bras. Cienc. Solo. 34, 709–716. https://doi.org/10.1590/S0100-06832010000300012.

Lynch, L. Root architecture and plant productivity. Plant Physiology, v.109, p.7-13, 1995. https://doi.org/10.1104/pp.109.1.7

Loreto, F., Velikova, V., 2001. Isoprene produced by leaves protects the photosynthetic apparatus against ozone damage, quenches ozone products, and reduces lipid peroxidation of cellular membranes. Plant Physiol. 127, 1781–1787. https://doi.org/10.1104/pp.010497.

Lynch, L., 1995. Root architecture and plant productivity. Plant Physiol. 109, 7–13. https://doi.org/10.1104/pp.109.1.7.

Mafes, 2017. Big mix AS-2, preparador de solo. 3p. http://mafes.com.br/big_mix.html, (accessed 05 May 2018).

Marshall, T.J., Holmes, J.W., Rose, C.W., 1996. Soil Physics. Cambridge University Press, United Kingdom.

Martino, D.L., and Shaykewich, C.F., 1994. Root penetration profiles of wheat and barley as affected by soil penetration resistance in field conditions. Can. J. Soil Sci. 74, 193–200. https://doi.org/10.4141/cjss94-027.

Matielo, J.B., Santinato, R., Almeida, S.R., Garcia, A.W.R., 2015. Cultura do café no Brasil. Manual de recomendações. Fundação Procafé. 590p.

Mendes, G.A., de Oliveira, M.A.L., Rodarte, M.P., de Carvalho Dos Anjos, V., Bell, M. J.V., 2022. Origin geographical classification of green coffee beans (*Coffea arabica* L.) produced in different regions of the Minas Gerais state by FT-MIR and chemometric. Curr. Opin. Food Sci. 5, 298–305. https://doi.org/10.1016/j.crfs.2022.01.017.

Mittler, R., 2002. Oxidative stress, antioxidants and stress tolerance. Trends Plant Sci. 9, 405-410. https://doi.org/10.1016/S1360-1385(02)02312-9.

Motta, A.C.V., Nick, J.A., Yorinori, G.T., Serrat, B.M., 2006. Distribuição horizontal e vertical da fertilidade do solo e das raízes de cafeeiro (*Coffea arabica* L.) cultivar Catuaí. Acta Sci. Agron. 28, 453–462. https://www.redalyc.org/articulo.oa?id=303026571005.

Nakano, Y., Asada, K., 1981. Hydrogen peroxide is scavenged by ascorbate specific peroxidase in spinach chloroplasts. Plant Cell Physiol. 22, 867–880. https://doi.org/10.1093/oxfordjournals.pcp.a076232.

Ning, T., Liu, Z., Hu, H., Li, G., Kuzyakov, Y., 2022. Physical, chemical and biological subsoiling for sustainable agriculture, Soil Tillage Res. 223, 105490. https://doi.org/10.1016/j.still.2022.105490.

Nunes, A.L.P., Cortez, G.L.D.S., Zaro, G.C., Zorzenoni, T.O., Melo, T.R.D., Figueiredo, A., Aquino, G.S., Medina, C.C., Ralisch, R., Caramori, P.H., Guimarães, M.D.F., 2021. Soil morphostructural characterization and coffee root distribution under agroforestry system with Hevea Brasiliensis. Sci. Agric. 78, e20190150. http://doi.org/10.1590/1678-992X-2019-0150.

Oliveira, I.P., Oliveira, L.C. Moura, C.S.F.T., 2012. Cultura de café: histórico, classificação botânica e fases de crescimento. Revista Faculdade Montes Belos.

Partelli, F.L., Cavalcanti, A.C., Menegardo, C., Covre, A.M., Gontijo, I., Braun, H., 2020. Spatial distribution of the root system of Conilon and Arabica coffee plants. Pesq. Agropec. Bras. 55, e01333. https://doi.org/10.1590/S1678-3921.pab2020.v55.01333.

Pimentel, C., 2004. A relação da planta com a água. Seropédica. Edur. 191p.

QGIS Development Team, 2021. QGIS Geographic Information System. Open Source Geospatial Foundation. https://qgis.org/en/site/.

R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.J., 2018. Soil structure as an indicator of soil functions: a review. Geoderma. 314, 122–137. http://dx.doi.org/10.1016/j.geoderma.2017.11.009.

Rejeb, K.B., Savouré, C.A.A., 2014. How reactive oxygen species and proline face stress together. Plant Physiol. Biochem. 80, 278-284. https://doi.org/10.1016/j.plaphy.2014.04.007

Saffari, N., Hajabbasi, M.A., Shirani, H., Mosaddeghi, M.R., Owens, G., 2021. Influence of corn residue biochar on water retention and penetration resistance in a calcareous sandy loam soil. Geoderma. 383, 114734. https://doi.org/10.1016/j.geoderma.2020.114734.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Araújo Filho, J.C., Oliveira, J.B., Cunha, T.J.F., 2018. Sistema brasileiro de classificação de solos. 5. ed. revisada e ampliada, Embrapa. Brasília. 356 p.

Sene, M. Vepraakas, M.J., Naderman, G.C., Denton, H.P., 1985. Relationships of soil texture and structure to corn yield response to subsoiling. Soil Sci Soc Am J. 49, 422–7. https://doi.org/10.2136/sssaj1985.03615995004900020030x

Serafim, M.E., Oliveira, G.C., CurI, N., Lima, J.M., Guimarães, P.T.G., Lima, V.M.P., 2013a Potencialidades e limitações de uso de Latossolos e Cambissolos, sob sistema conservacionista em lavouras Cafeeiras. Biosci J. 29, 1640–1652.

Serafim, M.E., Oliveira, G.C., Lima, J.M., Silva, B.M., Zeviani, W.M., Lima, V.M.P., 2013b. Disponibilidade hídrica e distinção de ambientes para cultivo de cafeeiros. Rev. Bras. de Eng. Agricola e Ambient. 17, 362–370. https://doi.org/10.1590/S1415-43662013000400002.

Serafim, M.E., Oliveira, G.C., Vitorino, A.C.T., Silva, B.M., Carducci, C.E., 2013c. Qualidade física e intervalo hídrico ótimo em Latossolo e Cambissolo, cultivados com cafeeiro, sob manejo conservacionista do solo. Rev. Bras. Cienc. Solo. 37, 733–742. https://doi.org/10.1590/S0100-06832013000300020.

Silva, B.M., Oliveira, G.C., Serafim, M.E., Silva, E.A., Guimaraes, P.T.G., Melo, L.B.B., Norton, L.D., Curi, N., 2019. Soil moisture associated with least limiting water range, leaf water potential, initial growth and yield of coffee as affected by soil management system. Soil Tillage Res. 189, 36–43. https://doi.org/10.1016/j.still.2018.12.016.

Silva, B.M., Santos, W.J.R., Oliveira, G.C., Lima, J.M., Curi, N., Marques, J. J.G.S.M., 2015. Soil moisture space-time analysis to support improved crop management. Cienc. e Agrotecnologia. 39, 39–47. https://doi.org/10.1590/S1413-70542015000100005.

Silva, É.A., Silva, S.H.G., Oliveira, G.C., Carducci, C.E., 2016. Root spatial distribution in coffee plants of different ages under conservation management system. Afr. J. Agric. Res. 11, 4970–4978. https://doi.org/10.5897/AJAR2016.11356.

Silva, E.A.D., Brunini, O., Sakai, E., Arruda, F. B., Pires, R. C.D.M., 2009. Influence of controlled water deficits on flowering synchronization and yield of coffee under three distinct edapho-climatic conditions of São Paulo State, Brazil. Bragantia. 68, 493–501. https://doi.org/10.1590/S0006-87052009000200024.

Silva, R.F., Severiano, E.C., Oliveira, G.C., Barbosa, S.M., Peixoto, D.S., Tassinari, D., Silva, B.M., Silva, S.H.G., Dias Júnior, M.S., Figueiredo, T.A.F.R., 2021. Changes in soil profile hydraulic properties and porosity as affected by deep tillage soil preparation and Brachiaria grass intercropping in a recent coffee plantation on a naturally dense Inceptisol. Soil Tillage Res. 213, 105127. https://doi.org/10.1016/j.still.2021.105127.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed.; USDA-NRCS: Washington, DC, USA.

Souza, G.S.D., Alves, D.I., Dan, M.L., Lima, J.S.D.S., Fonseca, A.L.C.C.D., Araújo, J. B.S., Guimarães, L.A.D.O.P., 2017. Soil physico-hydraulic properties under organic conilon coffee intercropped with tree and fruit species. Pesq. Agropec. Bras. 52, 539–547. https://doi.org/10.1590/S0100-204X2017000700008.

Teixeira, A.F.D.S., Weindorf, D.C., Silva, S.H.G., Guilherme, L.R.G., Curi, N., 2018. Portable X-ray fluorescence (pXRF) spectrometry applied to the prediction of chemical attributes in Inceptisols under different land uses. Cienc. e Agrotecnologia. 42, 501–512. https://doi.org/10.1590/1413-70542018425017518.

Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G., 2017. Manual de métodos de análise de solo, third ed. Empresa Brasileira de Pesquisa Agropecuária, (Embrapa), Brasília. 564p.

Thomaziello, R.A., Fazuoli, L.C., Pezzopane, J.R.M., Fahl, J.I., Carelli, M. L.C., 2000. Café arábica: cultura e técnicas de produção. Campinas. 82p.

Usman, A.A., Mamman, M.B.A., 2022. Spatio-Temporal Analysis of Dry Spell for Agricultural Decision Support in North-Central Nigeria. Environmental and Earth Sciences Research Journal, 9(1), 1-7. http://iieta.org/journals/eesrj.

Velikova, V., Yordanov, I., Edreva, A., 2000. Oxidative stress and some antioxidant systems in acid rain-treated bean plants. Plant Sci. 151, 59–66. https://doi.org/10.1016/S0168-9452(99)00197-1.

Verma, S., Dubey, R.S., 2003. Lead toxicity induces pilid peroxidation and alters the activities of antioxidant enzymes in growing rice plants. Plant Science, v. 164, p. 645-655. https://doi.org/10.1016/S0168-9452(03)00022-0

Weindorf, D. C., Chakraborty, S., 2020. Portable X-ray fluorescence spectrometry analysis of soils. Soil Science Society of America Journal. 84, 1384-1392. https://doi.org/10.1002/saj2.20151

Willekens, H., Inzé, D., Van Montagu, M., Van Camp, W., 1995. Catalases in plants. Mol. Breed. 1, 207-228. https://doi.org/10.1007/BF02277422.

WRB, I.W.G., 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Report No.106. FAO, Rome.

Yoder, R.E., 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. J. Agron. 28, 337–351.

Zanandrea, I., Alves, J.D., Deuner, S., de F.P., Goulart, P., Henrique, P.D.C., Silveira, N.M., 2010. Tolerance of Sesbania virgata plants to flooding. Aust. J. Bot., 57, 661–669. https://doi.org/10.1071/BT09144.

SUPPLEMENTAL FILES (MANUSCRIPT – II)

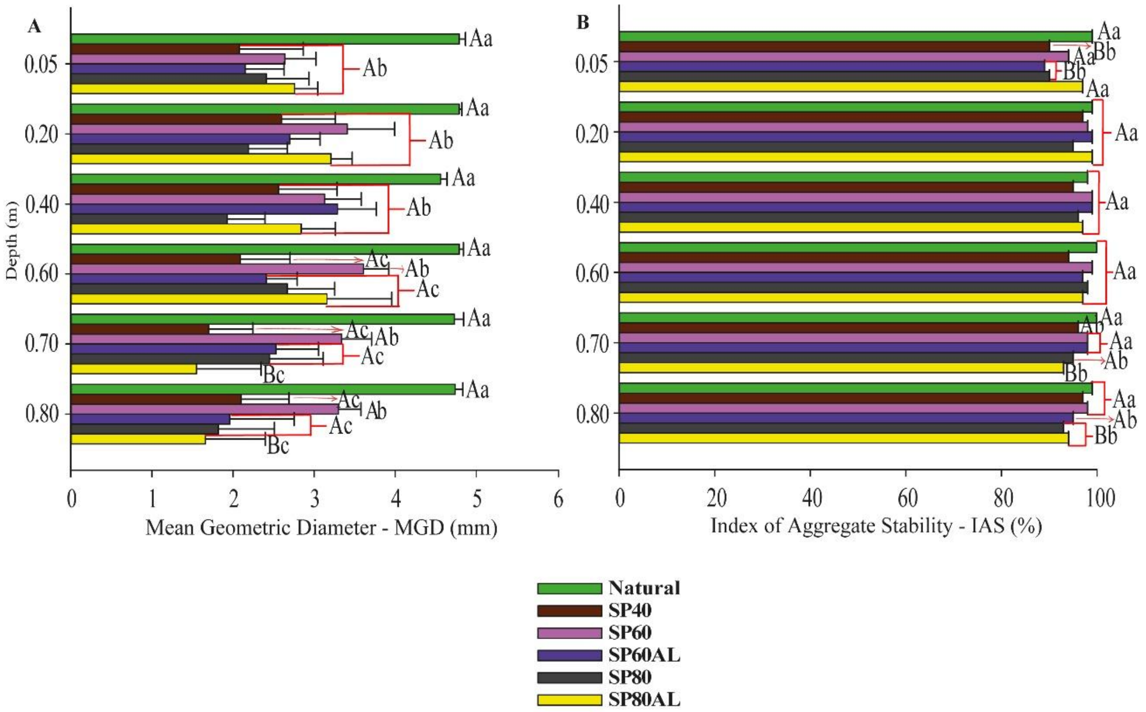


Figure 2. Soi aggregate stability index (IAS) and aggregate mean geometric diameter (MGD) as a function of different soil deep tillage strategies. SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer; SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler; Natural: a native savannah vegetation area from Cerrado biome and depths (0.05; 0.20; 0.40; 0.60; 0.70 and 0.80 m). Means followed by the same lowercase letter do not differ for treatments within the same depth, and the same capital letter does not differ from each other for depth within the same treatment by the Scott-Knott test ($p < 0.05$).

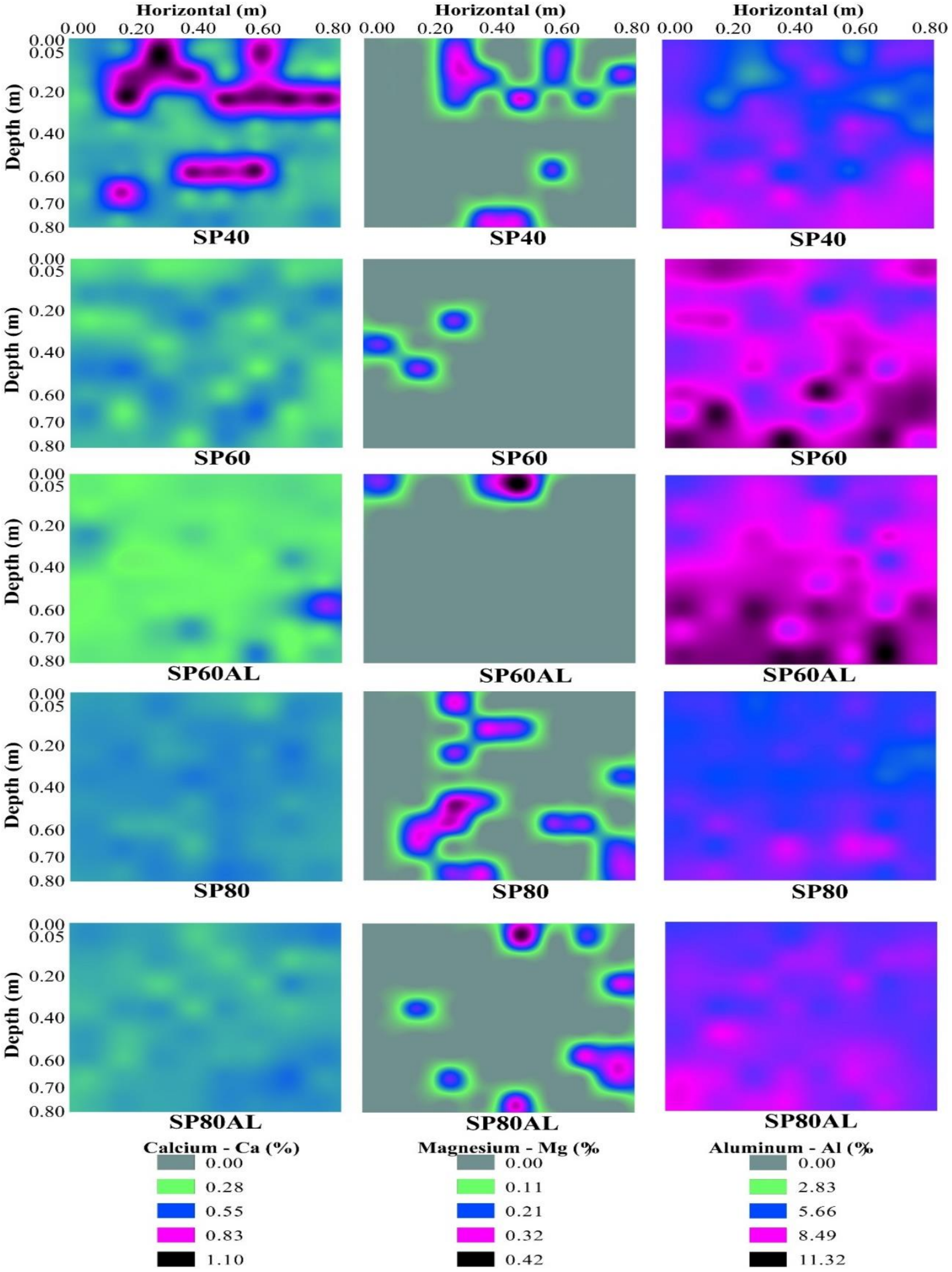


Figure 3. Element contents obtained by pXRF analysis of samples collected in the Cambisol profile (0.10 × 0.10 m grid) to characterize all soil preparations studied in terms of Ca (%), Mg (%), and Al (%) of this Cambisol for different soil preparations: SP40: planting furrow at 0.40 m with conventional fertilization using a furrower; SP60: planting furrow at 0.60 m with conventional fertilization and with additional liming (SP60AL) using a soil homogenizer;

SP80: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with additional liming (SP80AL) using both soil homogenizer and subsoiler.

MANUSCRIPT – III

(Manuscript formatted according to Soil and Tillage Research Journal guidelines)

Deep tillage and chemical amendment modify the structural physical of dense Cambisol inferred from X-ray computed tomography

Abstract: Successful coffee cultivation in Cambisol requires managing dense layers, nutrient restrictions, and water shortage. Therefore, deep tillage and chemical amendment strategies along the soil profile are necessary. This study aims to quantify changes and the impact of different soil preparation strategies on the structural quality of Cambisol by X-ray Computed Tomography (CT) and how these changes influence soil attributes correlated with coffee growth. The experiment was conducted on a commercial farm in Nazareno, Minas Gerais, Brazil, in a Cambisol area with a clay loam texture. A randomized block design experiment was performed with three blocks, and the following three soil preparations were investigated:
SP40: soil preparation with a furrower was used to open the planting furrow at 0.40 m depth with conventional fertilization + a mixture of gypsum, serpentinite, and natural phosphate; SP60: Big Mix (Soil homogenizer) was applied at 0.60 m with conventional fertilization + a mixture of gypsum, serpentinite, and natural phosphate; SP80: Soil homogenizer was employed at 0.60 m, followed by a Dreno (subsoiler) at 0.80 m with conventional fertilization + a mixture of gypsum, serpentinite, and natural phosphate. These soil preparations were compared to an area apart from the experimental site under native savannah vegetation from the Cerrado biome (Natural). Undisturbed samples using plexiglass cylinders were collected at depths of 0.175-0.225, 0.475-0.525, and 0.675-0.725 m six years after the initial soil preparation. These depths corresponded to the effective preparation of the furrower, soil homogenizer, and subsoiler (0.20, 0.50, and 0.70 m, respectively). In these samples, soil computer tomography analyses were investigated along with the correlation of plant measurements (stem diameter - SD, plant height - PH, and normalized difference vegetation index - NDVI). The experimental site also analyzed soil penetration resistance (PR), bulk

density (BD), root system growth variables, and chemical element contents with soil moisture monitoring and the NDVI data evaluated from October 2019 to March 2021. Analysis of variance and the Scott-Knott test ($p < 0.05$) was applied to all data analyzed. The surface mapping of the following PR, root variables, element contents, and the spatiotemporal mapping of soil water content were examined by kriging via geostatistical analysis, all done in the statistical software R. The CT technique revealed how different agricultural implements affected the structural quality of Cambisol. The subsoiler increased density, reducing inter-aggregates and void space while enhancing aggregate stability and porosity. The SP80M preparation, effective at 0.70 m depth, positively influenced soil properties and coffee plant growth. It led to lower penetration resistance, allowing for better root elongation, reflected in coffee plants' stem diameter, height, and normalized difference vegetation index (NDVI). In addition, deep tillage by the subsoiler and chemical amendments by the mixture improved the distribution of calcium, magnesium, and phosphorus, contributing to the enhancement of Cambisol's structural physical quality when related to the preparation of the planting furrow up to 0.40 m with the furrower and up to 0.60 m with the soil homogenizer.

Keywords: CT scan; Soil physics; Soil porosity; Soil structure; Subsoiler

1. Introduction

The Brazilian economy relies heavily on coffee, the most traded product globally (Silva et al., 2022). Minas Gerais is the leading producer of *Coffea Arabica* L., contributing over half of the country's total production (Conab, 2022). However, coffee-growing regions face environmental challenges, specifically dry periods, impacting plant development and production (Santos et al., 2014). In addition, climate change-induced drought is a significant concern (Silva et al., 2015). Therefore, implementing soil management strategies to address edaphic drought becomes crucial (Silva et al., 2019; Barbosa et al., 2021; Silva et al., 2021). The prolonged drought periods have resulted in lower crop production for Arabica coffee (Silva et al., 2015; Conab, 2022).

Deep tillage management strategies in Cambisols have received significant attention from researchers aiming to promote improved root system growth in crops (Medeiros et al., 2013; Silva et al., 2016a and b; Barbosa et al., 2020; Silva et al., 2021). The root system is crucial in plant development as it utilizes soil resources, including water and nutrients. Root architecture determines how the soil profile is exploited (Hou et al., 2022), especially in nutrient-deficient and highly acidic soils like Cambisols (Teixeira et al., 2018). Studies have shown that favorable chemical and physical soil conditions are vital for the rapid development of plants (Silva et al., 2015; Silva et al., 2019; Barbosa et al., 2020). Deep soil preparation and chemical amendment create an environment that enhances water and nutrient absorption, which is particularly crucial in coffee-growing regions facing prolonged drought periods (Santos et al., 2014; Silva et al., 2015; Conab, 2022).

Subsoiling practices have been employed to facilitate soil disruption, looseness, and root viability in the search for water availability (Medeiros et al., 2013; Barbosa et al., 2020; Silva et al., 2021), directly impacting coffee production (Santos et al., 2014). However, subsoiling practices can adversely affect subsoil structural modification (Carducci et al., 2017; Silva et al., 2021). Therefore, it is crucial to understand how roots respond to the spatial complexity of soils (Carducci et al., 2015), primarily when nutrient management strategies are implemented to enhance root exploration (Hou et al., 2022) and overall plant development (Barbosa et al., 2020). Additionally, the association between root behavior and penetration resistance (Carducci et al., 2015; Silva et al., 2019), as well as the influence of soil preparation on water storage (Silva et al., 2015), should be considered.

To better understand the impact of management practices on soil structure in coffee production, robust techniques like X-ray Computed Tomography (CT) imaging can assist (Carducci et al., 2014a and b; 2015; 2017; 2022). CT provides a detailed spatial characterization of soil components, allowing for a comprehensive understanding of soil structure and its functions (Dhaliwal and Kumar, 2022). This non-invasive technique has revolutionized soil science through 3D imaging (Carducci et al., 2015). Management practices in agricultural areas significantly influence soil structure dynamics, affecting root mobility, water storage, and plant nutrient availability (Carducci et al., 2015; Dhaliwal and Kumar, 2022). Consequently, the morphology and porosity of voids within aggregates, including their size, shape, and orientation, are altered (Taina et al., 2013; Costa et al., 2018; Pires et al., 2020; Carducci et al., 2022). Furthermore, understanding the effects of deep soil preparation and chemical amendment in coffee plantations on plant growth, particularly in height and vegetative vigor (NDVI), is crucial (Barbosa et al., 2020).

Our hypothesis, supported by CT technology, examines the impact of different agricultural implements (furrower, soil homogenizer, and subsoiler) at specific depths (0.20, 0.50, and 0.70 m) on the structural quality of Cambisols. The soil homogenizer and subsoiler aim to reduce soil density, improve porosity, and decrease penetration resistance by disrupting the dense layer. This condition will promote vigorous coffee plant growth and root expansion, facilitated by enhanced water storage and availability. Using X-Ray Computed Tomography and assessing physical properties, water storage, and coffee vigor, this study aims to evaluate changes in the structural quality of Cambisols resulting from different soil preparation strategies.

2. Material and Methods

2.1. Site of Study

The study was conducted in an experimental coffee plantation located in Nazareno municipality, part of the Alto Rio Grande Basin, Minas Gerais state, Brazil, with geographical coordinates latitude 21° 10' 52″ S and longitude 44° 39′ 04″ W (Figure 1) at an average altitude of 935 m. The soil at the site was classified as Cambissolo Háplico Tb distrófico (Santos et al., 2018), Typic Hapludept in Soil Taxonomy (Soil Survey Staff, 2014) and Dystric Cambisol (WRB, 2014). The soil had a clay loam texture with a moderate block structure and consisted of pelitic rocks and quartzite on granite gneiss (Figure 2). The local climate was classified as Cwb (Figure 1), indicating a humid temperate climate with dry winter and moderately hot summer (Köppen, 1936). The average annual temperature is 18.5°C, and the rainy season occurs from November to March, with an average yearly rainfall of 1350 mm. Before the experiment, the soil was chemically and physically characterized (Table 1).

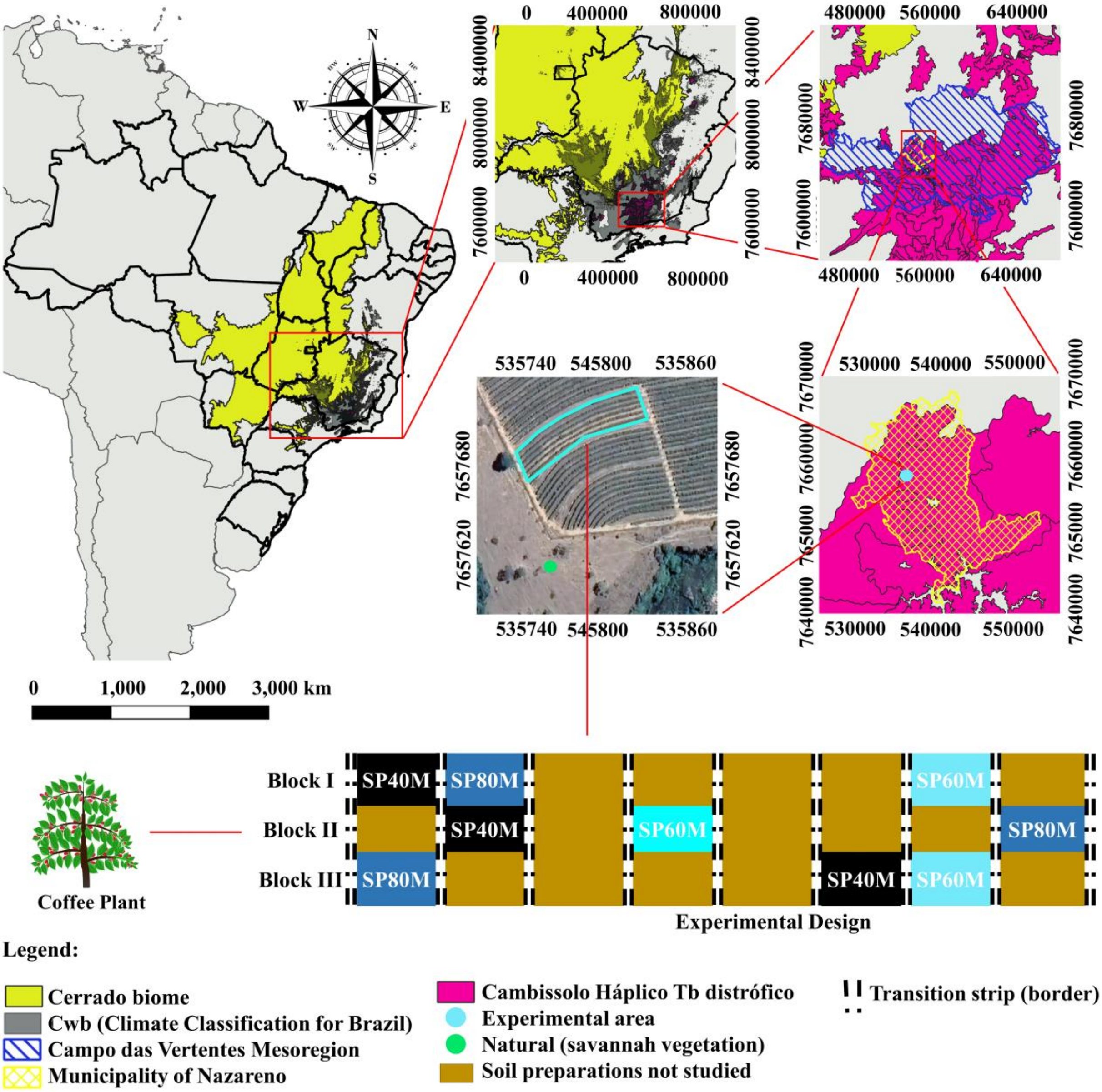


Figure 1. Location and design of the experimental area defined in UTM zones. SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler.

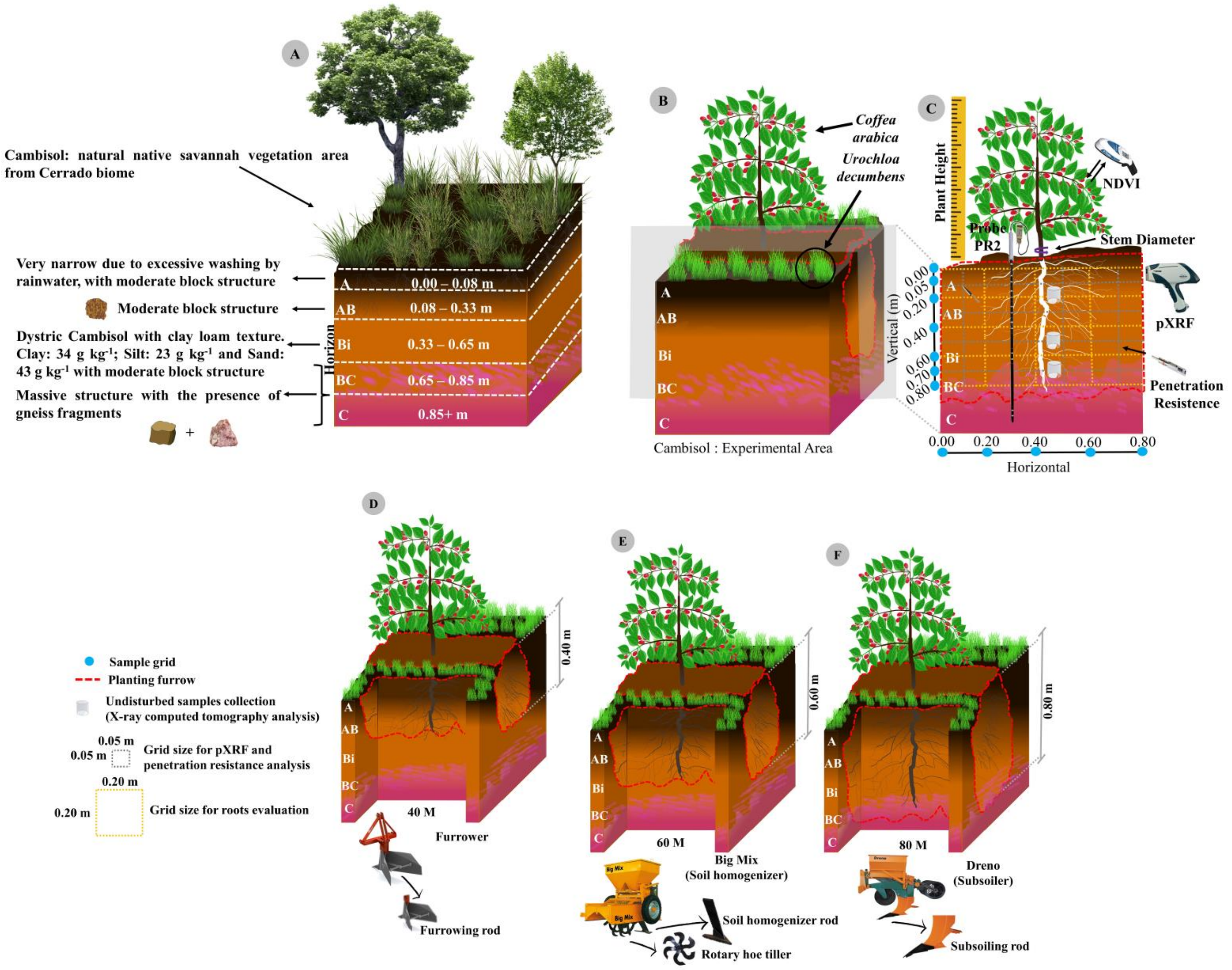

A
Cambisol: natural native savannah vegetation area from Cerrado biome
Very narrow due to excessive washing by rainwater, with moderate block structure
Moderate block structure
Dystric Cambisol with clay loam texture. Clay: 34 g kg-1; Silt: 23 g kg-1 and Sand: 43 g kg-1 with moderate block structure
Massive structure with the presence of gneiss fragments
+
Horizon
A 0.00 – 0.08 m
AB 0.08 – 0.33 m
Bi 0.33 – 0.65 m
BC 0.65 – 0.85 m
C 0.85+ m
B
Coffea arabica
Urochloa decumbens
A
AB
Bi
BC
C
Cambisol : Experimental Area
C
Plant Height
NDVI
Probe PR2
Stem Diameter
pXRF
Penetration Resistence
Vertical (m)
0.00
0.05
0.20
0.40
0.60
0.70
0.80
A
AB
Bi
BC
C
0.00
0.20
0.40
0.60
0.80
Horizontal
D
0.40 m
A
AB
Bi
BC
C
40 M
Furrower
Furrowing rod
E
0.60 m
A
AB
Bi
BC
C
60 M
Big Mix (Soil homogenizer)
Soil homogenizer rod
Rotary hoe tiller
F
0.80 m
A
AB
Bi
BC
C
80 M
Dreno (Subsoiler)
Subsoiling rod
Sample grid
Planting furrow
Undisturbed samples collection (X-ray computed tomography analysis)
0.05 m
0.05 m
Grid size for pXRF and penetration resistance analysis
0.20 m
0.20 m
Grid size for roots evaluation

Figure 2. Schematic representation of the Cambisol profile under natural Cerrado vegetation and its main pedological characteristics (A); Representation of the coffee crop in the experimental area (B); Representation of the collection of samples with preserved structure (structural physical-hydric quality and aggregates) in the planting furrow area follow by the penetration resistance, root system, soil moisture monitoring, pXRF evaluation and plant measurements (stem diameter, plant height, and NDVI) (C); Summary of the operations conducted in the present study, in each management of the experimental area (D, E, and F). SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler. Adapted from Silva et al. (2021).

Table 1. Mean values of soil fertility analyses and soil particle size distribution at the soil profile before planting the coffee crop in 2015.

Depth	pH	K	P	Na	Ca	Mg	Al	H+Al	SB	t	T	V	m	M.O.	P-Rem	Zn	Fe	Mn	Cu	B	S	Clay	Silt	Sand
(m)	(H_2O)	mg dm^{-3}			cmol$_c$ dm^{-3}							%		dag kg^{-1}	mg l^{-1}	mg dm^{-3}						g kg^{-1}		
0.00-0.20	5.1	22.7	0.4	2.0	0.4	0.1	0.2	3.2	0.6	0.8	3.7	15.9	28.8	2.3	13.4	0.9	61.1	5.8	1.8	0.7	6.0	33	16	51
0.20-0.40	5.5	16.7	0.3	2.7	0.3	0.1	0.1	2.8	0.4	0.5	3.2	13.1	19.9	1.9	8.0	0.6	40.3	2.3	1.7	0.2	5.1	33	23	44
0.40-0.60	5.8	11.3	0.1	2.0	0.3	0.1	0.0	1.9	0.4	0.4	2.3	18.9	0.0	1.5	3.4	1.0	27.2	1.6	1.5	0.2	5.0	35	22	43
0.60-0.80	5.7	12.0	0.0	2.0	0.4	0.1	0.0	1.8	0.5	0.5	2.4	22.7	0.0	1.0	3.1	0.7	32.0	2.5	1.5	0.1	4.6	37	27	36

pH: hydrogen potential determined in water; OM: Organic Matter; SB: Sum of bases; t: effective cation exchange capacity; T: potential cation exchange capacity; m: aluminum saturation; V: Base saturation; P-Rem: Remaining phosphorus. Adapted from Barbosa et al. (2020).

2.2. Soil Preparation

The soil chemical correction was performed based on the soil properties determined in table 1 before coffee planting. Sixty days before planting, dolomitic limestone was applied at 3 Mg ha^{-1} (1.5 g dm^{-3}) over the entire area. The dolomitic limestone had a total neutralizing relative power of 87 %, with CaO of 39.7 % and MgO of 13.38 %. Limig incorporation into the soil was done using a harrow implement with twenty discs, a cutting width of 0.35 m, and an average tractor power of 230 hp.

Three soil preparation strategies were implemented in a homogeneous area for coffee crop planting. These included furrower + mixture of gypsum, serpentinite, and natural phosphate (SP40M), soil homogenizer + mixture of gypsum, serpentinite, and natural phosphate (SP60M), soil homogenizer + subsoiler + mixture of gypsum, serpentinite, and natural phosphate (SP80AL) (Figure 2).

The furrower implement was used to create furrows with a width of 0.35 to 0.65 m and a depth of 0.40 m. It required a tractor with 60 hp and weighed around 105 kg. The Big Mix equipment, or soil homogenizer, had a rotary hoe tiller and a fertilizer box with a volume of 270 dm^3. It effectively blended and corrected the soil, operating at a width of 0.50 m and a depth of 0.60 m, with a tractor power of 85 hp (Mafes, 2017). The Dreno agricultural tool, designed to address deep-seated soil impediments, included a subsoiling rod with a preparation capacity of up to 0.90 m (effectively up to 0.80 m). It required a tractor with over 180 hp and operated at speeds of up to 6 km per hour, with a load capacity of 450 kg or 1.2 tons (Mafes, 2017). After opening the furrows to a depth of 0.40 m, they were closed using a two-rod subsoiler at 3 to 5 km per hour. In cases where furrows were opened to depths of 0.60 and 0.80 m, the Big Mix equipment, equipped with a specific attachment tool, was used to close the furrows.

All preparations received fertilization following coffee-growing recommendations

(Guimarães et al., 1999) and a mixture of 500 g of gypsum, 167 g of serpentinite, and 500 g of natural phosphate per linear meter of the furrow. This mixture was effectively mixed and incorporated from 0.20 to 0.60 m depth in each furrow using the soil homogenizer with a rotary hoe tiller and a coupling fertilizer box (Mafes, 2017). Exclusively for SP40M, the mixture was incorporated up to a depth of 0.40 m using a furrower, which limited the effective depth. The mixture's composition was determined based on the phosphorus concentrations, gypsum (calcium), and magnesium requirements outlined in table 1. Topdressing fertilizations were applied three times, with the first in February 2016, applying 0.004 kg of N and K_2O per plant every twenty days to increase nitrogen use efficiency and reduce losses, mainly through leaching.

To mitigate the effects of water erosion on the Cambisol group under undulating relief, conservation practices were adopted. A combination of mechanical terracing and vegetative cultivation of *Brachiaria decumbens* L. (*Syn. Urochloa*) between crop rows was implemented.

Cultural treatments were carried out to promote the coffee plant's overall development, including top-dressing fertilizers. In the 2018-2019 crop season, specific amounts of cover liming, N, K_2O, and P_2O_5 were applied per plant. In the 2019-2020 crop season, only N and K_2O were applied without cover liming. Finally, in the 2020-2021 crop season, cover liming and N, K_2O were applied per plant, corresponding to this study's evaluation year.

2.3. Experimental Arrangement

The experiment followed a randomized block design with three soil preparation strategies (SP40M, SP60M, SP80M). Each plot consisted of crop strips measuring 10.8 m wide and 84 m long (907.2 m^2), with fourteen plants along a planting line (10.5 m) for each soil preparation and three replications. The Catuaí Vermelho - IAC 99 coffee cultivar (*Coffea* *arabica* L.) was planted in December 2015. The spacing between plants was 0.75 m, and the distance between planting lines was 3.6 m, resulting in a density of 3,703 plants per hectare. Nine total rows inside the testing area were considered borders and not evaluated to minimize environmental effects and plot interaction. Data collection for soil X-ray CT scan, root systems, penetration resistance, soil physical characterization, element contents, water content monitoring, and plant measurements were performed randomly in the central plot strips.

2.4. Soil core sampling

In September 2021, almost six years after coffee implantation, soil samples were collected from the experimental coffee area and a native vegetation reference area (Natural), a native savannah vegetation area from the Cerrado biome (Figures 1 and 2). Trenches were opened, and undisturbed soil core samples were collected using metallic rings at six depths 0-0.05; 0.15-0.20; 0.35-0.40; 0.55-0.60; 0.60-0.70; 0.75-0.80 m. In addition, 54 samples were collected for physical-hydric characterization, considering three soil preparation strategies, six depths, and three blocks.

The undisturbed soil samples were gradually saturated with distilled water and then subjected to different matric potentials (-2, -4, -6, -8, and -10 kPa) using suction units and (-33, -100, -500, and -1500 kPa) in the Richards extractor (Teixeira et al., 2017). After reaching equilibrium, the samples were weighed and dried in a forced circulation oven. Soil density (BD) was calculated using the volumetric ring methodology (Teixeira et al., 2017), and the available water capacity was estimated based on the water content at field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) (Silva et al., 2015). The water content at field capacity was determined at a matric potential of -10 kPa (Lima et al., 2010).

Undisturbed soil samples were collected in plexiglass cylinders (0.06 m in diameter and 0.05 m in height) for CT scan analysis. The samples were collected at specific layers corresponding to the practical work of different agricultural machinery. The layers of interest were 0.175-0.225 m for the furrower, 0.475-0.525 m for the soil homogenizer, and 0.675-0.725 m for the subsoiler, representing effective depths (the middle of the plexiglass cylinder) of 0.20, 0.50, and 0.70 m, respectively.

Twenty-seven samples were collected inside the experimental area, including three depths, three soil preparation strategies, and three blocks. In the Natural area, only three cylinders were collected at the 0.175-0.225 m layer due to the presence of gravel, making sampling in the other layers unfeasible. This sampling only aiming at a depth of 0.20 m in the Natural is justified by the fact that this Cambisol has a naturally dense layer at a depth of 0.20 m, and therefore its evaluation due to the alteration promoted by different agricultural implements used in opening the furrow is supported. Thus, four treatments were studied (SP40M, SP60M, SP80M, and Natural), resulting in 30 samples for the CT scan analysis.

2.4.1. X-ray CT scanning

The soil samples were prepared and dehydrated in an oven at 40º C to remove water content and minimize interference with X-ray propagation. Tomographic images were obtained using a third-generation microtomography system (NIKON XT H 225 ST) with specific settings (Nikon Metrology, NV). The X-ray generation involved a tungsten filament and tungsten target at voltages of 225 kV and currents of two microamperes (Costa et al., 2016a and b).

The tomographic images were generated with a voltage of 150 kV and a current of 200 mA. Three thousand sixteen projections were acquired at an angular step of approximately 0.12°, with a spatial resolution of 35 μm. Each projection had an integration time of 500 ms and one frame per projection. The acquisition of each projection required two additional images and lateral displacement, resulting in a scan time of 1 hour and 45 minutes per sample. A copper filter of 0.5 mm thickness was used to minimize artifacts.

The images were reconstructed to create a cube with dimensions of 30 mm edge and 857 x 857 x 857 voxels (x, y, and z, respectively). The exact center of the reconstructed plexiglass cylinder was selected to ensure the evaluation of a uniform sub-volume for all samples and to correspond to the specific practical work depth of each machine under study (0.20, 0.50, and 0.70 m). The 3D model was created using specialized software, and X-ray attenuation in the CT scans was compared using VGStudio Max 2.2 program. The grey-scale values were converted to the Hounsfield scale (Carducci et al., 2014a), and image noise was reduced using a 3D Gauss filter. The final slices of the reconstructed images were generated in the same software program.

2.4.2. Image segmentation and processing

The segmentation process separates the region of interest, containing voids in the soil sample, from the rest of the image. This identification of voids, solids, and the soil matrix was made voxel by voxel, based on their radiodensity values using the Hounsfield scale (Costa et al., 2016a and b). Next, histograms were constructed for each image using the Batch processor, and an average histogram was generated from these individual histograms. Calculations and interpretations were then performed using the average histogram. Finally, individual semivariograms were computed for each image using the histogram data, and an average semivariogram was also generated for further analysis.

The histograms obtained from the 30 images were analyzed using the Fityk software, with the Gaussian model being selected due to its 96.8% accuracy. Ranges of values for void, non-void, non-solid, and solid phases were determined based on the peaks and variances of multimodal histograms constructed from the Gaussian curve. These values were then manually applied as thresholds in ImageJ using the threshold tool, allowing for a comparison with the original image. This step initiated the multiphase segmentation, identifying three distinct regions: voids, matrix, and solids.

The image processing followed a five-step methodology developed by the Laboratory of Soil Imaging at the U of G (Jefferies et al., 2014). The first step involved converting the original image into an 8-bit binary image, assigning values 1 or 2 to represent voids and non-voids, solids and non-solids, respectively. In the second step, a mask was created to analyze the soil matrix by assigning NaN values to voids and solids and 1 to the matrix. The third step multiplied the mask image with the original grayscale image, resulting in a matrix image with NaN values for voids and solids. The histogram of this segmented grayscale matrix image was then used to calculate the radiodensity of the soil matrix. In the fourth step, voids were identified using the "Particle Analysis" plug-in. The fifth and final step involved tabulating data from spreadsheets referencing tomographic data.

2.4.3. Morphometric analysis of voids

The void spaces in the soil samples were analyzed using a Batch processor and the "Particle Analyzer" plug-in. The plug-in created ellipsoids for each pore and determined their size and orientation based on their shape. The total voids were calculated by dividing the sum of small, medium, and large voids by the image size, multiplied by 100, where large voids (100001 - infinity voxels), medium voids (9 - 10000 voxels), and small voids (0 - 8 voxels). Large voids represented an inter-aggregate network of voids that spread across the soil aggregates. The intra-aggregate voids, categorized as medium and small voids, were calculated by dividing the sum of medium and small voids by the image size minus the number of large voids, multiplied by 100. The number of aggregates present in the sub-volume under study was determined by dividing the difference between the image size and the number of large voids by the image size, multiplied by 100. Finally, the surface area to volume ratio of inter-aggregate voids was calculated using the total surface area of the voids in pixels.

The medium and small voids, designated as intra-aggregate voids, were classified based on their shape, size, and orientation using parameters such as the major (a), intermediate (b), and minor (c) axes of the ellipsoid. The b/a and c/b ratios were calculated following Zingg's research (1935) and modified from Bullock et al. (1985). The voids were classified into prolate, oblate, triaxial, and equant shapes. However, the classification method may have difficulty determining the shape of voids due to the limitations of accounting for the voxels that make up a void axis. Therefore, in this study, such voids were classified as unclassified. The intra-aggregate voids were further divided into macro, meso, and microvoids based on their equivalent sphere diameter (size), according to Passoni et al. (2015). In this work, macrovoids referred to volumes greater than 2,268.1 x 10^2, mesovoids ranged from 4.189 x 10^2 to 1.023 x 10^{-3}, and microvoids were smaller than 1.278 x 10^{-4} mm^3. The orientation of the voids was determined in different directions, including inclined-horizontal (60-75° and 105-120°), near-horizontal (75-105°), inclined-vertical (15-30° and 150-165°), near-vertical (0-15° and 165-180°) and inclined (30-60° and 120-150°) as described by Taina et al. (2013). Therefore, using the ImageJ "Particle Analyze" tool through the Batch processor, voids were identified based on their shape, size, and orientation.

2.5. Root system

Soil trenches measuring 0.70 m (width) x 0.80 m (length) x 0.80 m (depth) were excavated using the cultural profile method to study root development. A vertical trench wall was maintained at 0.10 m from the plant stem under the canopy projection of the coffee plant.

In addition, the soil was scarified up to 0.05 m towards the interior to expose the roots, which were painted with a thin layer of white paint to enhance visibility (Carducci et al., 2014; Carducci et al., 2015).

A 0.2 x 0.2 m square grid was positioned parallel to the trench wall in front of the roots. Using a 14-megapixel digital camera, 2D images were captured. Considering the maximum depth of 0.80 m and the dimensions of the trench, 16 sampling points were generated. The images were processed and aligned in the free software ImageJ and then analyzed using the SAFIRA program (Jorge and Silva, 2010). This analysis provided variables such as root number (RN), root volume (RV) (mm^3), root surface area (RSA) (mm^2), root length (RL) (mm), and root diameter (RD) (mm). The root diameter was classified into fine roots ($Ø < 1$ mm), medium roots ($1 > Ø < 3$ mm), and thick roots ($Ø > 3$ mm), according to Motta et al. (2006).

2.6. Penetration resistance

The pocket penetrometer CL-700 from Soil test 2205 Lee Street, Chicago, Illinois, USA, manually measured the penetration resistance (PR). The penetrometer has a fixed cylindrical probe of 3.0 mm, inserted perpendicularly into the soil up to the reference mark. The reading was recorded in kgf cm^{-2} (Ajayi et al., 2009). The PR measurements were conducted in the same soil trenches as the root development study, using a grid with 0.10 x 0.10 m squares. Gravimetric soil water content U (g g^{-1}) was determined for each grid square, resulting in 64 samples of moisture and PR readings (8 depths x 8 measurements) for all soil preparation strategies.

The PR readings in kgf cm^{-2} were converted to MPa by multiplying them by 0.98066 since 1.0 kgf cm^{-2} equals 0.98066 MPa. To understand the behavior of PR concerning the gravimetric water content at the time of measurement for each management and depth, U_{10kPa}

(gravimetric water content at a matric potential of 10 kPa), which represents field capacity, was plotted. Soil density (BD) was also calculated using the data described in section 2.4.

2.7. Soil moisture monitoring

A profile probe PR2/6-SDI-12 from Delta-T Devices Ltd., Cambridge, UK was used to monitor the vertical distribution of soil moisture. This non-destructive method was applied at depths of 0.10, 0.20, 0.30, 0.40, 0.60, and 1 m to evaluate the temporal variability of soil moisture. In addition, four access tubes were installed in each soil preparation between the coffee plants in the planting row at the middle of the furrow. Readings were taken fortnightly from October 2019 to March 2021. The purpose was to identify periods and depths of water deficit, understand soil water storage variability, and examine its consumption by the coffee plants (Silva et al., 2015 subjected to different deep tillage practices.

The readings from the profile probe were based on the permittivity of the soil water content, which measures the material's response to polarization in an electromagnetic field, resulting in a stable voltage output in millivolts (mV). These readings were converted to volts (V) and soil moisture (m^3 m^{-3}) using polynomial conversion combined with soil calibration.

$$\theta_V = [1.125 - 5.53V + 67.17V^2 - 234.42V^3 + 413.56V^4 - 356.68V^5 + 121.53V^6] - a_0/a_1$$

(Equation 1)

Where: V is the value resultant in a stable voltage output in volts, a_0 and a_1 are the calibration coefficients, being $a_0 = 1.6$ and $a_1 = 8.4$ related to mineral soils with the organic matter content below 7% and bulk density above 1.0 Mg m^{-3} (Delta-T Devices, 2016).

A map of the monitoring of moisture over time (MMOT) was created based on the obtained soil moisture values. This map determined the available water classification using the soil physical-hydraulic data described in section 2.4. The classification was based on the following criteria: soil moisture values greater than 0.35 m^3 m^{-3} were considered easily drainable water, values between 0.35 and 0.25 m^3 m^{-3} were classified as plant-available water, and values less than 0.25 m^3 m^{-3} were considered strongly retained water.

2.8. pXRF

Soil chemical element contents were analyzed along the soil profile using a grid with 0.80 m intervals horizontally and vertically, resulting in 64 soil samples (8 depths x 8 samples). The samples were air-dried, sieved, and examined using pXRF Bruker, model S1 Titan LE, which has an X-ray tube of 50 keV and 100 μA and a silicon drift detector with a resolution of < 145 eV. To ensure accuracy, certified samples from the pXRF manufacturer (check sample) and the National Institute of Standards and Technology (NIST) (2710a and 2711) were scanned and compared with their certified contents. Recovery values (content obtained by pXRF/certified content) for different elements were measured, and a value of 0 indicates the absence of an accredited value or the equipment's lack of results for that element. Each soil sample was analyzed in triplicate for 60 seconds using Geochem software in Trace mode (dual soil) (Weindorf; Chakraborty 2016).

2.9. Plant measurement

During soil sampling, measurements of stem diameter (SD) and plant height (PH) were taken for each plant (12 useful plants) under soil preparation strategies. In addition, the vegetative vigor was assessed using the Normalized Difference Vegetation Index (NDVI), which quantifies vegetation growth Bhandari et al. (2012).

The NDVI was assessed using a Green Seeker® sensor (model RT200) from Ntech Industries (Barbosa et al., 2020). Readings were taken fortnightly alongside soil moisture monitoring, starting in October 2019 and ending in March 2021. The sensor was positioned 0.40 m before each coffee plant in all studied soil preparations. Two readings were conducted for each plant in each plot of the planting line, totaling 12 readings per plot.

2.10. Data analysis

The data were treated as a split plot with two factors, soil preparer strategies (plot) and depths (split-plot). Furthermore, Natural was treated as a reference area to evaluate the effects of the other soil preparations, SP40M, SP60M, and SP80M. An analysis of variance was performed to compare the treatments studied. When significant, the Scott-Knott test ($p < 0.05$) was applied to compare the mean values between SP40M, SP60M, and SP80M, and the Dunnett test ($p < 0.05$) was applied to compare the SP40M, SP60M, and SP80M to the reference area (Natural), performed using the R statistical program (R Core Team, 2021).

For the root data, was considered the maximum value for root number (RN), average for root diameter (RD), and sum for root volume (RV), root surface area (RSA), and root length (RL). Spatial analyses of the root system, PR, and soil elemental contents were conducted using the Multilevel B-splines interpolation (Lee et al., 1997) method in QGIS 3.16.13 software (QGIS Development Team, 2021). The MMOT maps were generated using Surfer software version 13, employing the kriging module to interpolate soil water content values (Usman et al., 2022). The resulting surface response was imported into a geographic information system, categorizing water content classes based on volumetric water content ranging from < 0.05 to > 0.40 $m^3 m^{-3}$, following the minimum and maximum moisture values obtained from PR2/6-SDI-12 readings (Silva et al., 2015).

The surface maps were created to visualize the distribution of root variables and soil penetration resistance along the soil profile for the proposed soil preparation strategies of the planting furrow after almost six years of coffee plantation. The water content maps aimed to assess the variability in different deep tillage practices during the period of October 2019 to March 2021. For elemental contents mapping, only elements associated with the chemical amendment (mixture) and soil acidity conditions were selected (Ca, Mg, P, and Al). These maps provide insights into the disposition and concentrations of these elements resulting from adopting the practice and soil preparation over six years. Pearson correlation analysis evaluated the relationship between X-ray microtomography, physical properties, and coffee plant measurements using R's stats and *corrplot* packages (R Core Team, 2021; Wei and Simko, 2021).

3. Results and discussion

3.1. Radiodensity

At a depth of 0.20 m, the use of the furrower in soil preparation resulted in lower soil radiodensity (9.93%) and matrix (3.39%) compared to other soil preparations (Figure 3). The furrower, commonly employed by coffee farmers in Minas Gerais state, Brazil, promotes soil preparation up to 0.40 m depth. Research conducted in the same area at the end of the second coffee cycle showed that the furrower improved aeration and drainage pores at 0.20 m depth, enhancing porosity (Barbosa et al., 2020). However, after 18 months, the furrower induced compaction at the bottom of the planting furrow from 0.35 to 0.55 m depth at this Cambisol (Silva et al., 2021). This condition explains the increased soil and matrix radiodensity at 0.50 m depth compared to SP60M (8.27% and 2.76%, respectively). Still, no significant difference was observed at 0.70 m depth.

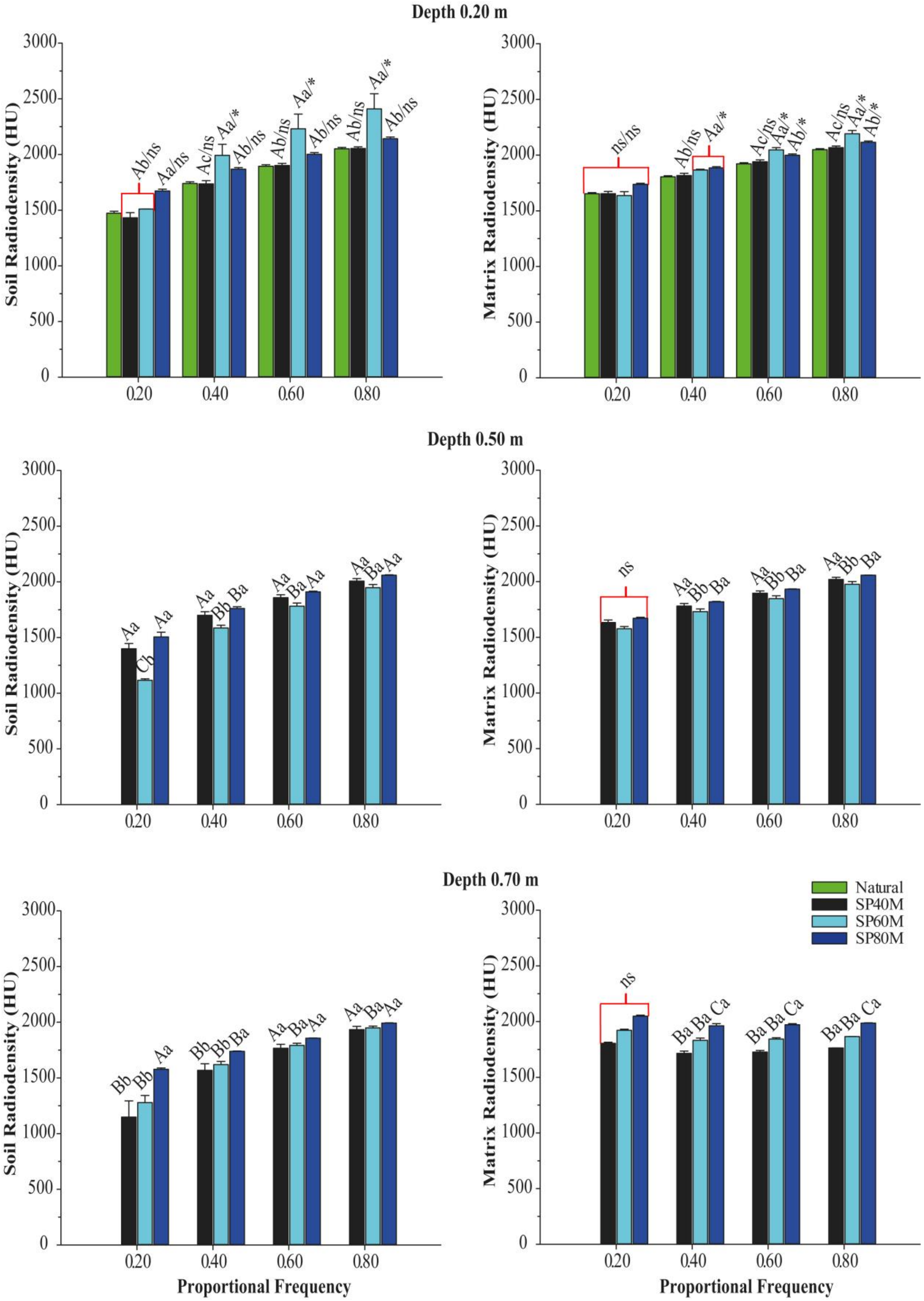


Figure 3. Soil and matrix radiodensity at different treatments and depths. SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and

natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler; Natural is a native savannah vegetation area from Cerrado biome. Bars followed by the same lowercase letters do not differ by the Skott-Knott test ($p < 0.05$) and compare the preparations (SP40M; SP60M, and SP80M) with each other. Bars followed by an * differ from each other by Dunnett's test ($p < 0.05$), ns: not significant by the F test ($p < 0.05$) when compared to the reference area (Natural).

SP60M at a depth of 0.50 m exhibited lower soil radiodensity (9.42%) and matrix (3.68%) compared to the other soil preparations (Figure 3). However, it was found that the soil homogenizer, with the rotary hoe tiller, caused compaction at the furrow's bottom from 0.55 to 0.80 m depth (Silva et al., 2021). The result obtained in this study is attributed to the chemical amendment applied until 0.60 m depth, which was not examined in the previous research. Additionally, combining additional liming with soil homogenizer until 0.60 m depth reduced soil density in the 0.40 to 0.60 m layers, unlike the same preparations without additional liming (Barbosa et al., 2020). Evidence suggests that deep tillage and chemical amendment improves the soil's structural integrity for coffee production by promoting root expansion and enhancing water accessibility (Carducci et al., 2015; Silva et al., 2016c), which is crucial in mitigating prolonged droughts expected in the Cerrado Mineiro region of Brazil (Silva et al., 2015).

Unlike the other machinery investigated, the subsoiler did not demonstrate the expected structural relief response regarding subsoiler effectiveness at 0.70 m depth, as it resulted in increased soil and matrix radiodensities (8.06% and 3.45% on average, respectively) in figure 3. However, it should be noted that these contributions are only evident when considering the different depths within each soil preparation strategy. At 0.70 m depth, SP80M exhibited lower matrix radiodensity compared to 0.50 m and 0.20 m depths, which may be attributed to the soil preparation response and the mixture's incorporation. This finding aligns with the results reported by Barbosa et al. (2020), where the use of the subsoiler in combination with chemical amendments in-depth led to a decrease in density throughout the soil profile (0.05 to 0.80 m), significantly improving the physical-hydraulic quality of the Cambisol. The authors noted that the same effect was not observed when using the subsoiler without chemical amendments.

The density results in figure 3 of the soil and matrix, measured in Hounsfield units (HU), generally indicate a significant reduction in radiodensity as the depth of tillage increases using different machinery, particularly the subsoiler suggesting that as the planting furrow deepened, there was better loosening, turning, and breaking of the soil in depth. Cambisols inherently possess low effective depth (Medeiros et al., 2013) and high density (Pereira et al., 2010), which can range from 1.25 to 1.42 Mg dm^3 (Silva et al., 2018). Failing to address these properties through deep tillage management strategies (Barbosa et al., 2020; Silva et al., 2021) can lead to crop yield losses due to insufficient soil aeration (Reynolds et al., 2009), thereby limiting the development of coffee plants (Silva et al., 2021).

Managing the dense Cambisol layer is crucial for promoting the growth of coffee plants in terms of height and vigor (Barbosa et al., 2020). Adopting management practices that improve physical-hydric properties can enhance these outcomes (Silva et al., 2021). X-ray CT imaging provides a three-dimensional perspective on the micrometric scale, allowing for a better understanding of how agricultural management affects soil structure (Carducci et al., 2014a). In addition, this method enables conclusions regarding the production system's sustainability (Carducci et al., 2022).

3.2. Void morphometry

The total void volume analysis (Figure 4C) reveals that SP40M at a depth of 0.20 m exhibits a higher total void volume than SP60M and SP80M, with an average difference of 13.64% and 108.33%, respectively, considering the range of treatments within each depth. At a depth of 0.50 m, SP60M has an average of 76.19% more void space than SP80M. Brewer (1976) states soil structure encompasses solid particles and voids' size, shape, and arrangement. Elliott and Coleman (1988) emphasize that void space refers to the volume of soil not occupied by solid particles and is closely related to pore size distribution, which is vital for the soil's physical properties, as highlighted by Houston et al. (2017). The void space, which pertains to pore size, shape, and connectivity, plays a crucial role in water movement, aeration, and root development, especially for coffee plants (Carducci et al., 2015; Silva et al., 2015). Therefore, the quantitative characterization of porosity and voids for evaluating the soil's microstructure, as emphasized by Taina et al. (2008), holds significant relevance.

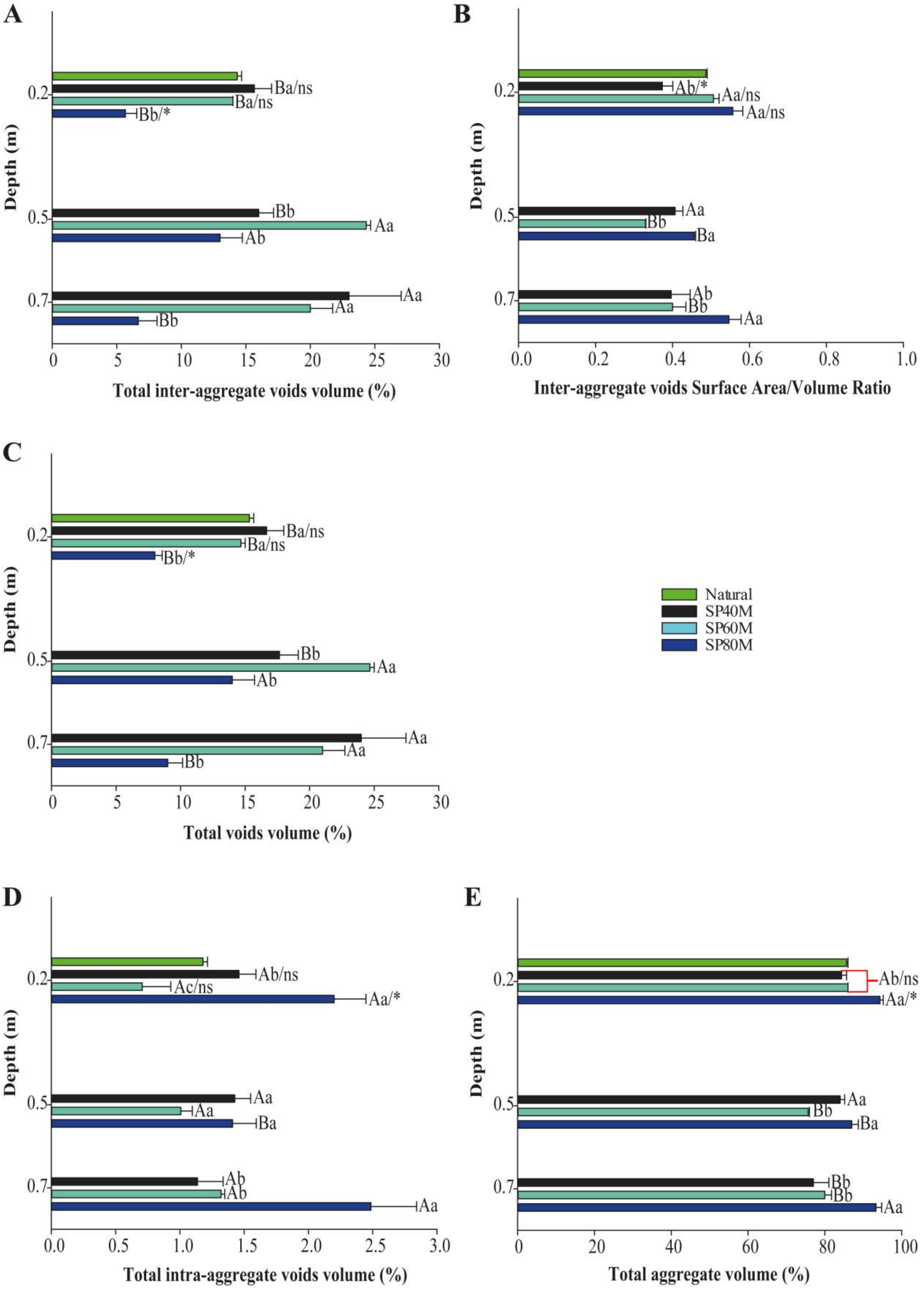


Figure 4. Void morphometry at different treatments and depths. SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural

phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler; Natural is a native savannah vegetation area from Cerrado biome. Bars followed by the same lowercase letters do not differ by the Skott-Knott test ($p < 0.05$) and compare the preparations (SP40M; SP60M, and SP80M) with each other. Bars followed by an * differ from each other by Dunnett's test ($p < 0.05$), ns: not significant by the F test ($p < 0.05$) when compared to the reference area (Natural).

In contrast, at a depth of 0.70 m, the SP80M exhibited a significant decrease in the total percentage of voids compared to SP40M and SP60M, with an average reduction of 60%. This decrease is attributed elaborately to the performance of the subsoiler. According to Wilding and Lin (2006), a reduction in void space indicates soil degradation caused by compaction. Xu et al. (2018) demonstrate that high pressure, such as the extreme action of the traffic-related passage under high moisture conditions, contributes to removing void space. They justify this phenomenon based on their study using CT techniques to assess hydrologically active pores. However, it is essential to note that the soil homogenizer and the subsoiler caused compaction at the bottom of the planting furrow, specifically from 0.55 to 0.80 m and 0.75 to 0.80 m, respectively. This compaction has been confirmed by Silva et al. (2021) and described by Barbosa et al. (2020) as an operational error resulting from the entry of machinery outside the zone of soil friability.

The decrease in void space observed in figure 4C corresponds to the higher radiodensity observed in SP80M (Figure 3) discussed previously. Botta et al. (2010) argue that intensive machine traffic can induce soil compaction, particularly under high moisture conditions, which is supported by their research on soybean production and deep soil preparation using a plow and subsoiler. Carducci et al. (2017) discuss how intensive agricultural management strategies often alter soil structure, sometimes resulting in negative implications, with soil depth and evaluation methods critical factors in understanding this scenario.

However, the changes in void space observed in figure 4C can be associated with the root number (RN) and root diameter (RD) shown in figure 5. The presence of roots tends to decrease the void proportion of the soil because roots play a crucial role in modifying the hydraulic properties of soil. This condition is attributed to the alterations that root tissues cause in the soil structure by occupying pore spaces and influencing pore size distribution (Ng et al., 2016). The decrease in void space for SP80M promoted an increase in RN (averaging ≤ 190) and the development of fine roots (Ø < 1 mm). On the other hand, the increase in voids for SP60M led to a reduction in RN (averaging < 70) and the development of medium-sized roots (1 mm > Ø < 3 mm). Thick roots, on the other hand, verified mainly by the SP60M, indicate changes in the hydraulic properties of the soil. According to Alaoui and Helbling (2006) that 74 to 100% of the water flow can preferentially occur through the channels of thick roots. Corroborating with this result, the research by Pierret et al. (2007) states that the roots modify the physicochemical properties of the soil, producing exudates that form organomineral complexes that facilitate respiration and soil decompression.

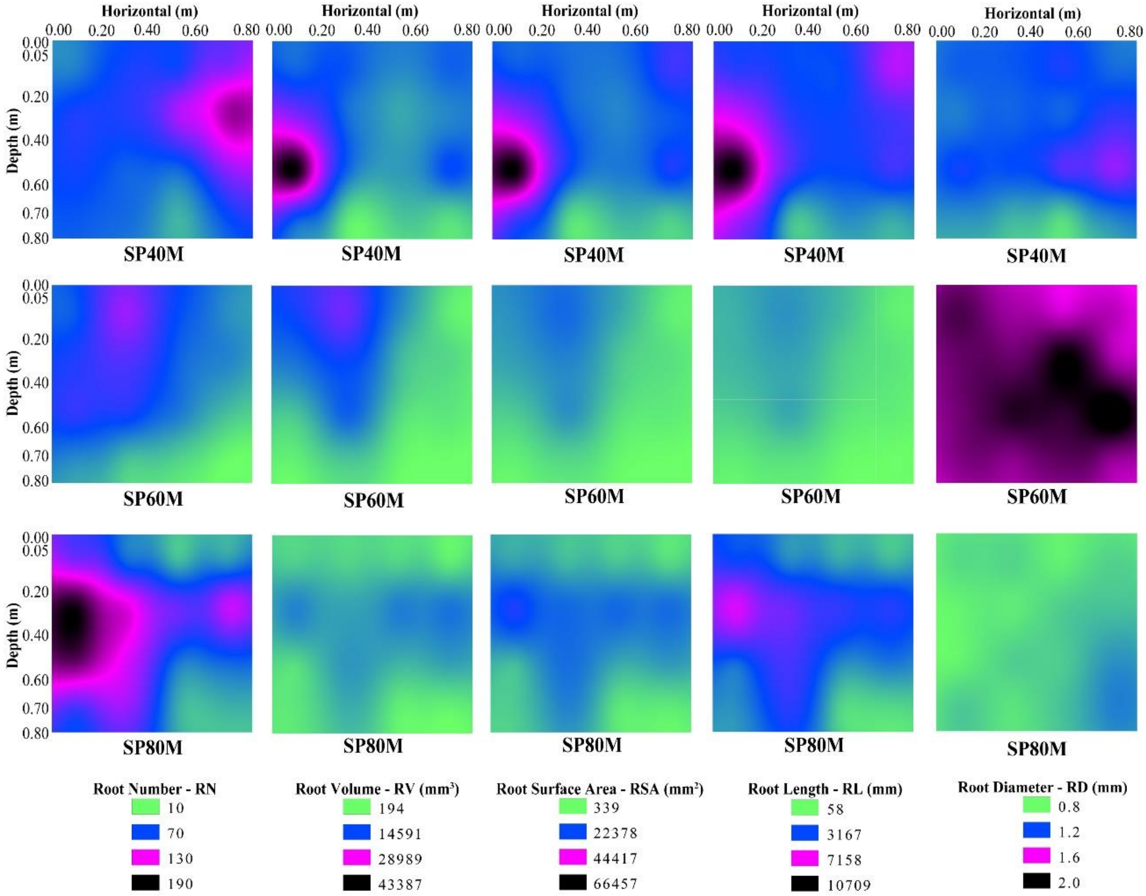


Figure 5. Maps of spatial variability of the coffee root system (RN root number; RV root volume: mm^3; RSA root surface area: mm^2; RL root length: mm; RD root diameter: mm) for different managements: SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler.

Moreover, SP80M was the only management approach that favored the occurrence of fine roots along the soil profile of this Cambisol, with a root diameter (Ø) of ≤ 0.8 mm. This association with the subsoiler's preparation has also been highlighted by Medeiros et al. (2013) in their study of deep subsoiling in a subsurface-compacted Typical Hapludult under a citrus orchard. This finding is significant because fine roots are physiologically important (Jesus et al., 2006) and are commonly found in Cambisols under coffee crops (Serafim et al., 2013b). Additionally, roots with a diameter of ≤ 0.8 mm are more efficient in water and nutrient absorption, making them essential for ecosystem functioning and soil properties due to their high membrane permeability (Campos-Cascaredo et al., 2021). Furthermore, intensive root exploration in the soil facilitates the search for nutrients and water (Hou et al., 2022).

The analysis of figure 4E reveals that SP80M exhibits a higher total aggregate volume than Natural at 0.20 m and the other soil preparations (SP40M; SP60M) across different depths, with an average increase of 11.91%. Soil structure refers to the arrangement of sand, silt, and clay particles into aggregates of various sizes, and the stability of these aggregates is essential for supporting the soil under stress (Nunes et al., 2020).

Evaluating soil structure quality often involves assessing the stability of soil aggregates, which can provide insights into the response of Cambisols to agricultural management practices and environmental factors (Silva et al., 2016a and b). Previous studies by Serafim et al. (2013b) and Carducci et al. (2015) support our findings, demonstrating that improvements in aggregation, particularly at deeper depths, can be attributed to factors such as gypsum percolation and the growth of coffee plant roots (Carducci et al., 2017).

Understanding changes in porosity with depth, and their effects on intra-aggregates and inter-aggregates are crucial in soil research. This can be achieved through computed tomography (CT) technology, which enables examining soil properties at millimeter resolutions, as highlighted by Oliveira et al. (1998) in their study of Brazilian soils. By utilizing CT technology, researchers can gain valuable insights into the changes in porosity and aggregation within the soil profile, providing a comprehensive understanding of soil structure and its implications for agricultural systems.

At a depth of 0.20 m, SP80M exhibited higher average intra-aggregates of 50.68% and

86.44% compared to SP40M and Natural, respectively (Figure 4D). Additionally, SP80M showed lower average inter-aggregates of 63.83% and 60.47% compared to SP40M and Natural, respectively (Figure 4A). At a depth of 0.50 m, SP80M (subsoiler) had lower inter-aggregates than the soil homogenizer, with an average decrease of 46.58%. When considering the depth variation within each treatment, the isolated effect of SP80M contributed to a reduction of inter-aggregates. At 0.70 m, the subsoiler resulted in larger intra-aggregates and lower inter-aggregates than the other soil preparations. The strength of connections between aggregates, which constitute the pore space of the soil, plays a crucial role in determining the changes in soil structure. The integrity of aggregates is related to the saturation level of the pore space inside them (Aluko and Koolen, 2001).

According to Othmer et al. (1991), intra-aggregates are responsible for water retention and availability to plants, while inter-aggregates play a role in root aeration and water drainage in the soil, particularly associated with fast water emptying and flow. Inter-aggregates are also linked to structural pores and are relevant to soil structure. On the other hand, individualized or discontinuous pores, which can occur within intra-aggregates or between inter-aggregates, are not directly related to soil structure (Carducci et al., 2022). However, understanding the impact of management practices and plant growth on pore space and aggregate soil organization requires a comprehensive evaluation method such as Computed Tomography (Carducci et al., 2017).

Despite a reduction in inter-aggregates, which could potentially affect aeration, root development (Figure 5) was not negatively impacted by soil preparations. The root growth parameters, such as RV, RSA, and RL, remained within acceptable ranges (< 14591 mm^3, < 22378 mm^2, and < 7158 mm, respectively), regardless of the soil preparations studied. This condition suggests that soil aeration may not have been lower than the critical threshold of 0.10 m^3 m^{-3}, which is known to limit root zone yield (Reynolds et al., 2009). Penetration resistance - PR (Figure 6) reveals that the furrower and soil homogenizer resulted in 1.50 ≥ PR ≤ 2.00 MPa values from the 0.20 m layer to 0.80 m depth. However, PR values close to 2.00 MPa were observed from 0.20 to 0.60 m. In contrast, the soil homogenizer followed by the subsoiler resulted in PR values ≤ 1.50 MPa along the soil profile.

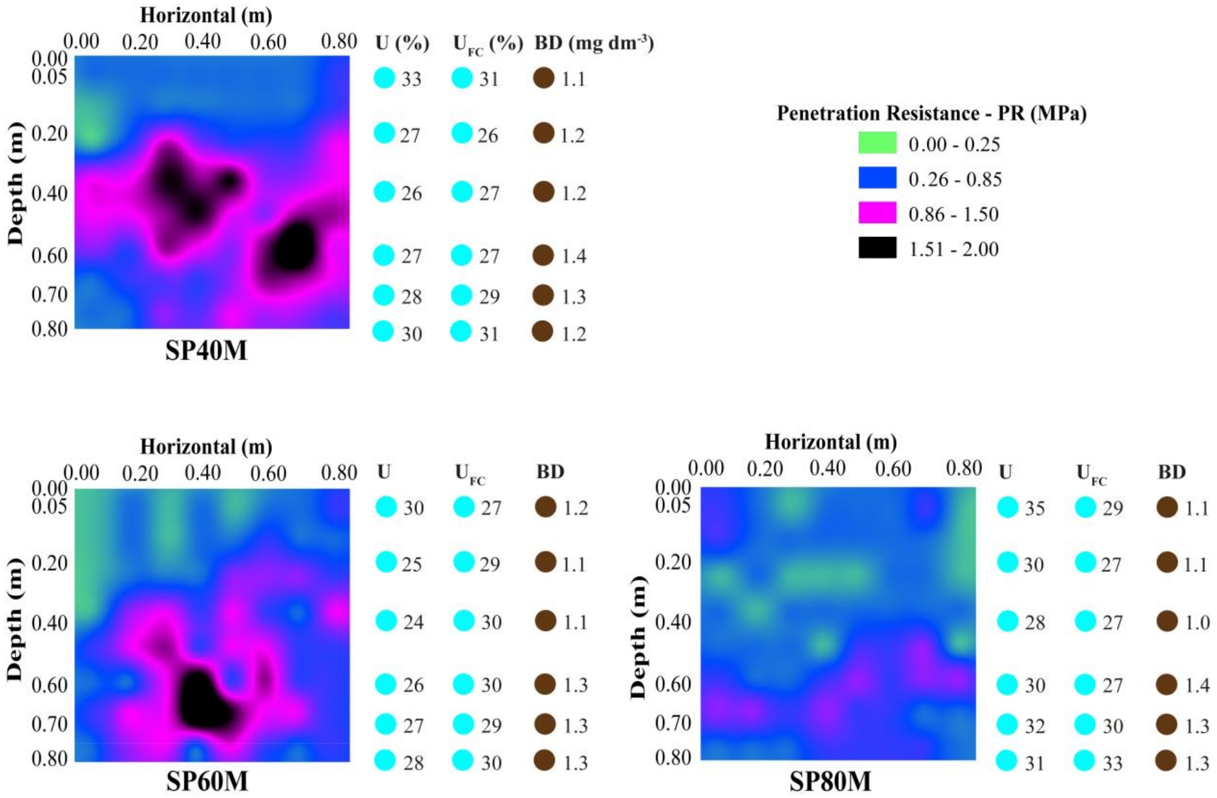


Figure 6. Maps of spatial variability of penetration resistance (PR) in MPa for different managements: SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler.

A PR value of 2.00 MPa was found to be a limiting factor for root growth, especially when the soil moisture content (U%) was close to field capacity (U_{FC}%). The spatial distribution of root variables (Figure 5), particularly for SP40M and SP60M, did not coincide with the areas where higher PR values were recorded, indicated by darker-colored places on the PR maps (Figure 6). The limitation of root variables was observed corresponding to the layers where PR values approached 2.00 MPa and areas with bulk density (BD) values ≥ 1.3 $mg.dm^{-3}$. These findings align with the research by Saffari et al. (2021), where 2.0 MPa was identified as the permissible limit for PR in most crops. Therefore, soil management practices strongly influence PR and depend on soil characteristics and machinery used (Silva et al., 2019).

The deep tillage using the soil homogenizer at 0.60 m and the subsoiler at 0.80 m depth improved the soil's physical quality, particularly regarding aggregation and water retention. These changes in soil structure, influenced by equipment and soil chemical amendments, are particularly relevant in coffee plantations (Barbosa et al., 2020; Silva et al., 2021; Carducci et al., 2021). The higher volume of intra-aggregates induced by the subsoiler (Figure 4C), despite a greater volume of aggregates (Figure 4E) overall, can be attributed to its higher radiodensity and reduced void space. This result is favorable if it does not hinder plant water availability (Barbosa et al., 2020). Increased soil water retention, especially in the surface layer (0-0.20 m), benefits coffee plants and promotes higher root activity (Silva et al., 2015). The subsoiler's role in breaking dense soil layers makes the contributions of SP80M management significant. This preparation helps create more uniform pores, aids in the distribution of homogenous pores throughout the soil profile (Carducci et al., 2017; 2021), and promotes the formation of deep roots (Carducci et al., 2015).

The subsoiler reduced aeration and drainage at 0.20 and 0.70 m depths by decreasing the inter-aggregates amount (Figure 4A). This result contradicts the findings of Barbosa et al. (2020), who found that using a subsoiler and chemical amendment improved aeration and water availability in this same Cambisol two years after planting. However, our results align with Carducci et al. (2017), who studied Oxisol under coffee plantations and observed that soil preparation practices, such as subsoiling and mixing layers, can cause significant disruption to the soil structure, particularly between depths of 0.20 and 0.80 m. These practices act as a subsoiler when opening the soil and the Big Mix when mixing the layers, resulting in severe aggregate rupture (Carducci et al., 2014b). Thereby, soil preparation in agricultural regions modifies the soil structure to varying degrees depending on the management techniques, depth, cultivation duration, and climate zone (Carducci et al., 2017).

The subsoiler's preparation at a depth of 0.70 m promotes higher water retention due to favoring intra-aggregates over inter-aggregate voids. This results in lower drainage and slower emptying of pores (Othmer et al., 1991). Figure 7B, MMOT supports this by showing increased soil water storage during the rainy season, particularly for θ values less than 0.25 m^3 m^{-3}, starting from a depth of 0.70 m. However, θ values range from 0.20 to 0.25 m^3 m^{-3} during the dry season. Additionally, figure 5 indicates that SP80M is the sole water source available for plants at a depth of 0.90 m, with a RN of 130 and a RL below 7158 mm until a depth of 0.80 m (Figure 5). These findings are significant as the subsoiler ally with chemical amendments serves as a deep preparation strategy to mitigate issues caused by soil drought (Silva et al., 2015; Barbosa et al., 2020).

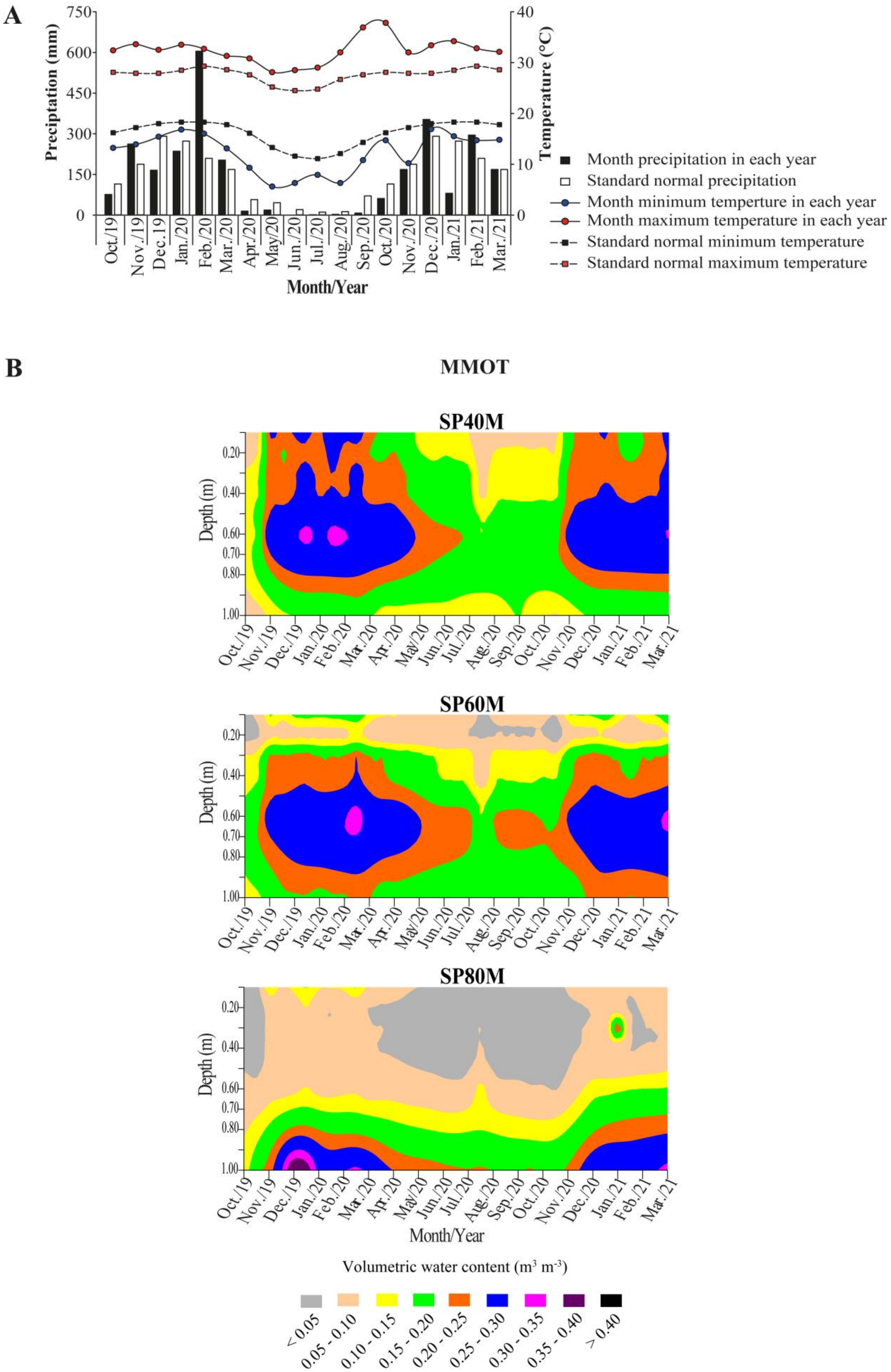

A
Precipitation (mm)
750
600
450
300
150
0
Temperature (°C)
40
30
20
10
0
Oct./19
Nov./19
Dec./19
Jan./20
Feb./20
Mar./20
Apr./20
May/20
Jun./20
Jul./20
Aug./20
Sep./20
Oct./20
Nov./20
Dec./20
Jan./21
Feb./21
Mar./21
Month/Year
Month precipitation in each year
Standard normal precipitation
Month minimum temperture in each year
Month maximum temperature in each year
Standard normal minimum temperature
Standard normal maximum temperature
B
MMOT
SP40M
SP60M
SP80M
Depth (m)
0.20
0.40
0.60
0.70
0.80
1.00
Month/Year
Volumetric water content (m³ m⁻³)
< 0.05
0.05 - 0.10
0.10 - 0.15
0.15 - 0.20
0.20 - 0.25
0.25 - 0.30
0.30 - 0.35
0.35 - 0.40
> 0.40

Figure 7. 2019 to 2021 data from São João del Rei weather station (21.25° S, 44.24° W) and climatological standard normals from the period 1981-2010. Source: INMET, 2022. Maps of spatial and temporal variability of the soil moisture monitoring over time (MMOT) of this Cambisol for different managements: SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler.

Still, regarding figure 4B, SP80M showed higher inter-aggregate voids surface area/volume than SP40M and SP60M, regardless of depth, with an average increase of 45.57%. Aggregate size and stability, which can reflect soil composition, were discussed by Rabot et al. (2018). The specific surface area of aggregates is an indicator of soil structure condition. It has been used by Zhu et al. (2016) in CT analyses to assess microstructures after natural soil regeneration. Arthur et al. (2013) found that increased surface area signifies improved aggregate structure. This finding is important because Silva et al. (2021) noted that larger and more stable aggregates enhance soil resilience to erosion, which is crucial for Cambisols, as they are highly prone to this problem of soil loss and degradation.

Consequently, despite the subsoiler causing higher radiodensity (Figure 3), reduced void space (Figure 4C), decreased inter-aggregate porosity (Figure 4A), and increased intra-aggregate voids (Figure 4D), the soil's structural physical quality was not negatively affected. On the contrary, the aggregate surface area increased (Figure 4B), indicating improved aggregated structural quality (Arthur et al., 2013; Zhu et al., 2016). Therefore, changes in soil structure directly impact aggregate distribution, stability, and morphometry and subsequently affect the porous system, water dynamics, air movement, penetration resistance, and root system (Barbosa et al., 2020; Silva et al., 2021).

3.3. Intra-aggregate voids porosity

The SP80M is the most favorable option for improving soil porosity, regardless of depth. It effectively classifies the size of intra-aggregate voids in the soil, resulting in lower microvoids and higher macrovoids compared to the Natural at a depth of 0.20 m (approximately 37.25% and 120%, respectively). Furthermore, the subsoiler surpasses the furrower and soil homogenizer by increasing mesovoids by an average of 6.25% at 0.20 m and 12.28% at 0.50 m. However, the SP60M exhibits the poorest condition at 0.50 m, with higher microvoids, lower mesovoids, and macrovoids than the other soil preparations (approximately 46.67%, 12.90%, and 70.83%, respectively). Conversely, at a depth of 0.70 m, the SP80M shows lower microvoids and higher macrovoids than SP40M and SP60M (approximately 37.28% and 146.15%, respectively) (Figure 8).

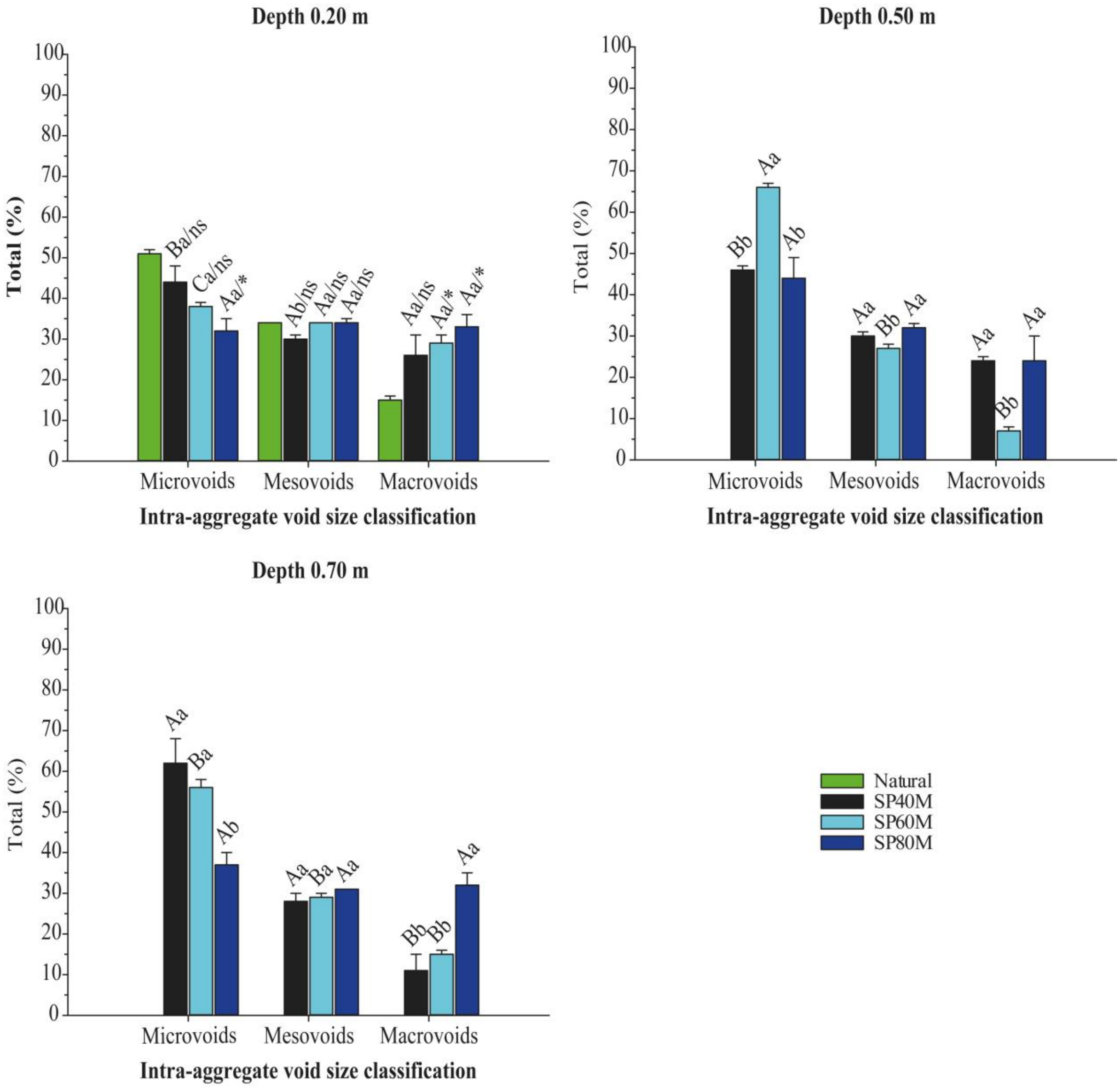


Figure 8 Intra-aggregate void size classification at different treatments and depths. SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler; Natural is a native savannah vegetation area from Cerrado biome. Macrovoids refers to volume > 2,2681 x 10^2 mm^3, Mesovoids 1,023 x 10^{-3} mm - 4,189 x 10^0 mm^3, and Microvoids < 1,278 x 10^{-4} mm^3. Bars followed by the same lowercase letters do

not differ by the Skott-Knott test ($p < 0.05$) and compare the preparations (SP40M, SP60M, and SP80M) with each other. Bars followed by an * differ from each other by Dunnett's test ($p < 0.05$), ns: not significant by the F test ($p < 0.05$) when compared to the reference area (Natural).

The alteration of intra-aggregate voids porosity is influenced by the preparation and effectiveness of implementing operations at different depths. For example, at a depth of 0.50 m, and 0.70 m, the soil homogenizer and subsoiler operations, respectively, have shown significant effects (Figure 4E) on aggregation and macroporosity (Figure 8) (Silva et al., 2016a, b, and c). This condition indicates faunal activity and improved root development based on soil management practices (Carducci et al., 2017), as supported by figure 5. The increase in density (Figure 3), reduction of void space (Figure 4C), and lower inter-aggregate voids (Figure 4A) did not have a disadvantageous effect due to the enhancements in intermediate pores, which improved the physical-hydric properties of Cambisol (Silva et al., 2021). Promoting macro and mesopores over micropores is crucial as it encourages significant root system growth and plant water uptake (Carducci et al., 2015; Silva et al., 2015). Improvements in macroporosity also lead to better water infiltration (Barbosa et al., 2020), while mesoporosity associated with inter-aggregate pores contributes to hydraulic conductivity, water storage, and plant availability (Dalmago et al., 2009).

The subsoiler's deep preparation and adding chemical amendments through the mixture are associated with changes in soil porosity, size, and shape. Studies by Santos et al. (2014) and Silva et al. (2015) reveal that subsoiler and soil homogenizer tillage and chemical correction up to a depth of 0.60 m, mainly through adding Ca^{2+}, improve physical and chemical properties. These improvements include enhanced structural quality and increased base saturation in the subsoil. Understanding the spatial geometry of pores is crucial in comprehending the dynamics of water processes influenced by management practices in agricultural production systems, as highlighted by Carducci et al. (2015).

3.4. Intra-aggregates voids shape

Regarding the shape of intra-aggregate voids (Figure 9), the unclassified shape shows a higher occurrence than triaxial, prolate, oblate, and equant shapes, regardless of depth and treatments. However, at a depth of 0.20 m, where treatments varied within each depth, SP60M exhibited a higher proportion of oblate-shaped voids than the other soil preparations (averaging 14.77%). At a depth of 0.50 m, SP60M showed lower triaxial and higher prolate-shaped voids (averaging 8.52%) compared to the different soil preparations. The oblate and equant shapes did not significantly differ among the soil preparations. At a depth of 0.70 m, both SP60M and SP80M contributed more to the morphometry of unidentified pores than SP40M (averaging 5.28%), while the triaxial shape remained unchanged. The subsoiler operation reduced the occurrence of prolate and equant-shaped voids at the same depth (averaging 33,97%) but favored oblate-shaped voids (averaging 20.37%) compared to the furrower and rotary hoe tiller operations.

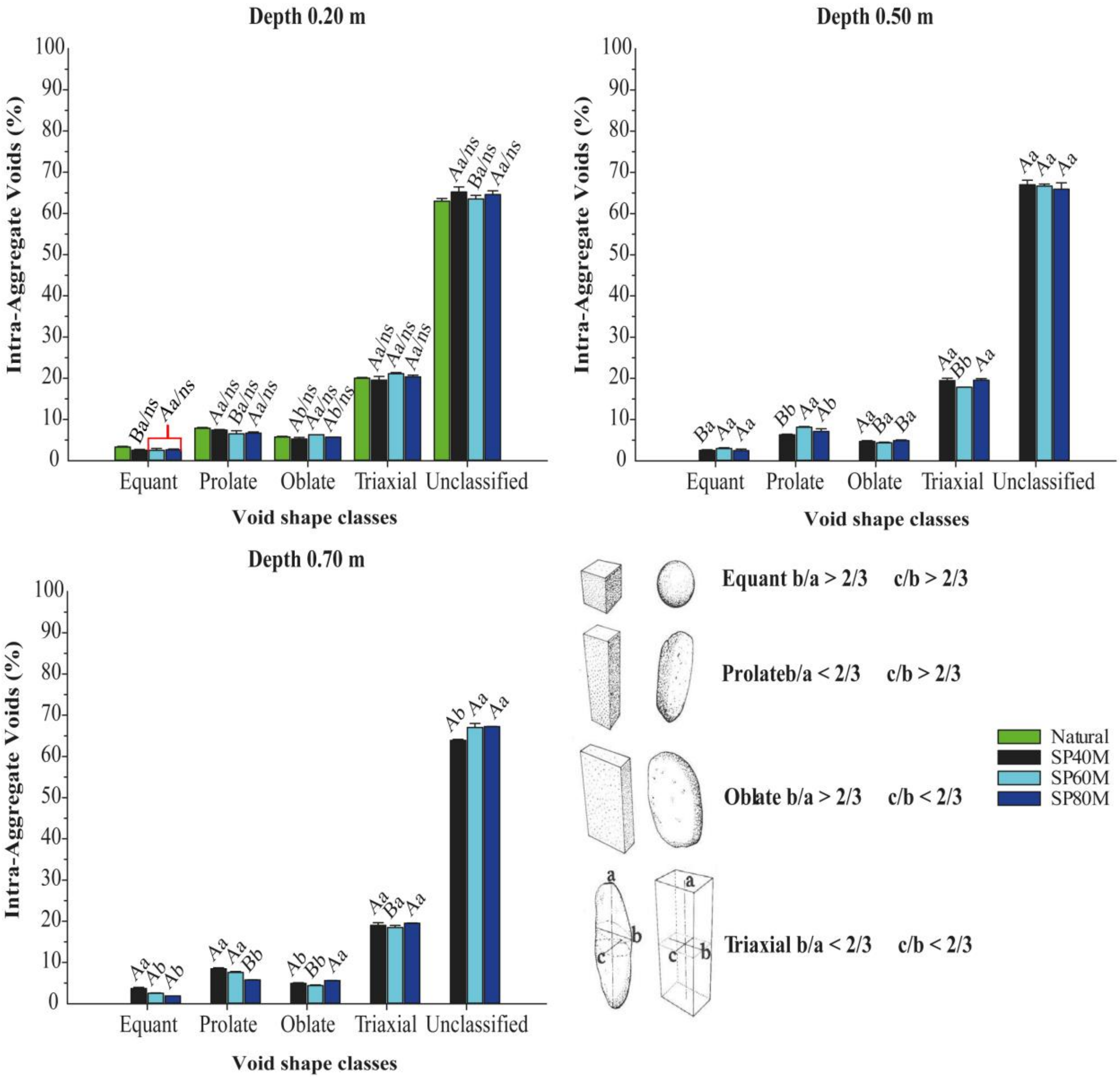


Figure 9. Intra-aggregates voids shape classification at different treatments and depths. SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler; Natural is a native savannah vegetation area from Cerrado biome. Unclassified: When not counting the voxels that make up an empty axis, which makes it difficult to determine its shape. Bars followed by the same lowercase letters do not differ by the Skott-Knott test ($p < 0.05$) and compare the preparations (SP40M, SP60M, and SP80M)

with each other. Bars followed by an * differ from each other by Dunnett's test ($p < 0.05$), ns: not significant by the F test ($p < 0.05$) when compared to the reference area (Natural).

Unclassified voids have implications for root exploration (Borges et al., 2019), wetting and drying cycles, soil management impact (Pires et al., 2017), and water movement in the soil, as described by Pires et al. (2019b). Carducci et al. (2022) define unclassified voids as packing pores that do not meet the criteria established by Zingg (1935), as mentioned in Bullock et al. (1985), and these pores play a crucial role in determining soil structure. However, Costa et al. (2018) demonstrate that a lower proportion of pore complexity leads to reduced root development and decreased water infiltration rate. On the other hand, the presence of triaxial (laminar, planar, or ellipsoidal), oblate (irregular or discoid chamber), prolate (tubular or rod-like), and equant voids (spheroidal), as defined by Bullock et al. (1985) and Zingg (1935), indicates the soil's quality status, as highlighted by Carducci et al. (2022).

Triaxial-shaped intra-aggregate voids are commonly found in expansive clays and are associated with block structures that have developed during soil formation (Taina et al., 2010; Taina et al., 2013). In addition, triaxial voids indicate the alteration and arrangement of soil particles (Pires et al., 2019b). Surprisingly, our data reveal that the soil homogenizer preparation reduced triaxial-shaped voids at a depth of 0.50 m, despite having lower soil and matrix radiodensity (Figure 3). However, this reduction can be attributed to the compaction induced by this implement at the bottom of the furrow (Barbosa et al., 2020; Silva et al., 2021). Arasan et al. (2011) discussed the relationship between the increased prevalence of rod-like pores and elongated voids, which disrupts the continuity of complex voids and leads to the formation of isolated pores due to soil compaction, supporting our findings. However, contrary to the results of Barbosa et al. (2020), Silva et al. (2021), and Carducci et al. (2022), the subsoiler did not favor the development of rod-like pores, despite SP80M showing higher radiodensity (Figure 3). This discrepancy may be due to Dreno's positive impact on structural physical quality, which includes decreasing soil density and promoting a beneficial reorganization of the soil structure, particularly concerning pores involved in water availability for plants, primarily through chemical amendments at greater depths.

The presence of tubular pores is strongly correlated with increased burrowing fauna and root activity, influenced by pore connectivity (Carducci et al., 2014a; Pires et al., 2020). In SP40M, smaller tubular and larger irregular pores are observed, which can be attributed to the limited root expansion caused by the furrower management (Figure 5). However, the subsoiler did not promote the occurrence of tubular pores throughout the soil profile. According to Pires et al. (2020), pores' size and shape significantly impact plant water availability and root development, which can vary depending on soil type and management practices. Comparing SP80M to SP40M, the lowest occurrence of equant-shaped intra-aggregate voids was observed at a depth of 0.70 m. Spherical pores are associated with soil structural deterioration and contribute to rounding aggregate edges (Lima et al., 2012).

The presence of circular-shaped aggregates indicates the impact of agricultural implements on soil structure (Carvalho et al., 2010). "Aggressive" soil management strategies can lead to the circularity of aggregates, which can affect root development in coffee plants (Carducci et al., 2015; Silva et al., 2015; Silva et al., 2016c). However, in the current study, combining the subsoiler and mixture incorporation demonstrated beneficial effects, as it did not lead to excessive circularity. Previous research by Silva et al. (2016b) found that increased calcium in the soil, along with the reorganization of the soil structure, improved aggregate stability and promoted root development (Silva et al., 2016c). These findings are consistent with the study conducted by Silva et al. (2016a), which showed that applying high doses of gypsum as a top dressing in Cambisols prepared up to 0.60 m depth increased calcium levels and positively influenced coffee plants.

Costa et al. (2018) indicate that a lower occurrence of complex pores can lead to reduced root growth and slower water infiltration rates. This observation is consistent with the response of SP40M management at 0.50 m depth, where a higher volume of unclassified intra-aggregate voids shape was favored, affecting RV, RSA, and RL ($\leq$ 43387 mm^3; $\leq$ 66457 mm^2 and $\leq$ 10709 mm, respectively). The compaction caused by the Big Mix implementation resulted in reduced growth of all root variables (Figure 5), decreased storage capacity, and limited water availability (Figure 7), particularly when compared to SP40M. As compressive stresses can cause more significant damage to layers beyond the effective depth of agricultural implements (Silva et al., 2021), these outcomes directly affect pore size, reducing pore connectivity and altering water infiltration rates (Pires et al., 2020). Prolate-shaped intra-aggregate voids indicate more excellent biological activity, improved water and airflow, and reduced penetration resistance, contributing to root development. This condition is demonstrated by the SP80M treatment, as shown in figures 5 and 6.

3.5. Orientation of Intra-Aggregate Voids

Figure 10 compares intra-aggregate void inclinations among the different soil preparations studied, considering the various treatments within each depth. At 0.20 m depth, SP80M showed an increase in inclined-vertical and inclined orientations (on average 14.35%) compared to the other management strategies and the natural condition. In contrast, the subsoiler reduced the inclined vertical at 0.50 m depth (on average, 11.57%). At 0.70 m depth, SP80M exhibited a higher frequency of near-vertical orientation (on average, 11.64%) and a decrease in inclined-horizontal intra-aggregate orientation (on average, 6.19%) compared to SP40M and SP60M.

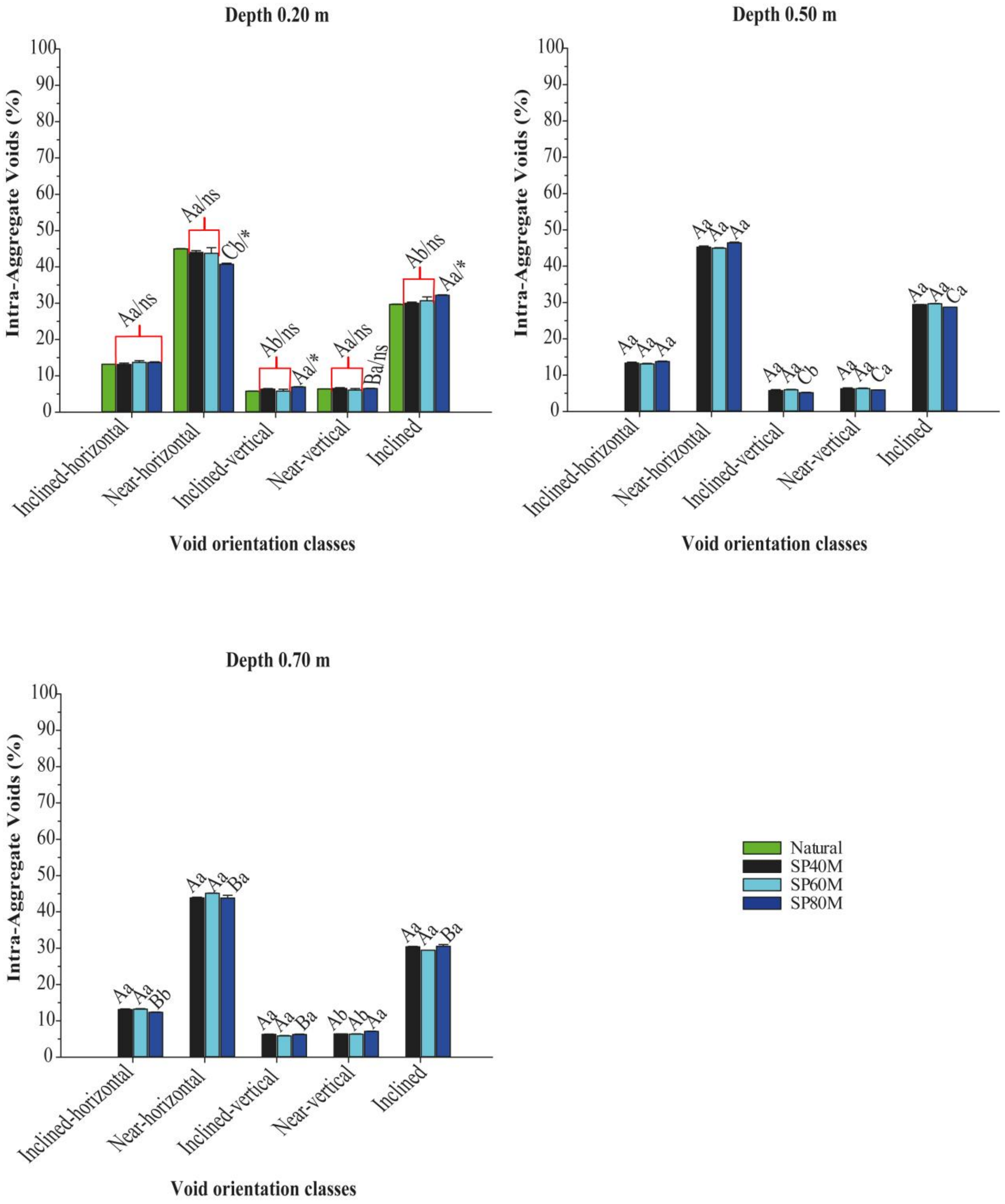


Figure 10. Orientation of intra-aggregate voids at different treatments and depths. P40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional

fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler; Natural is a native savannah vegetation area from Cerrado biome. Bars followed by the same lowercase letters do not differ by the Skott-Knott test ($p < 0.05$) and compare the preparations (SP40M, SP60M, and SP80M) with each other. Bars followed by an * differ from each other by Dunnett's test ($p < 0.05$), ns: not significant by the F test ($p < 0.05$) when compared to the reference area (Natural).

According to Costa et al. (2018), a preference for horizontal pores indicates more excellent soil compaction and higher penetration resistance. This observation aligns with the results shown in figure 10, where a lower occurrence of horizontal pores, particularly with SP80M management, was associated with enhanced root development (Figure 5), attributed to lower PR and BD values (Figure 6). The absence of physical barriers in the soil promotes increased root growth and macrofauna activity due to the vertical orientation of pores (Dowuona et al., 2009). This verticality directly affects water infiltration in the soil (Jassogne et al., 2007), as the pore orientation and tortuosity are crucial for the plant's ability to expand its root system in search of water and nutrients (Costa et al., 2018), as also confirmed by figure 7. Therefore, as Carducci et al. (2022) explained, our results demonstrate a diverse range of pore shapes and orientations throughout the soil profile resulting from management practices. Deep roots are necessary to access water and nutrients in the subsoil (Pires et al., 2019a), and combined with the increased nutrient availability provided by the mixture's incorporation, they directly benefit the survival rate of coffee plants (Barbosa et al., 2020).

Agricultural management practices significantly impact the soil's structural dynamics, influencing nutrient availability, which is crucial for plant growth (Rabot et al., 2018Furthermore, SP80M shows the most favorable distribution of calcium (Ca) content within the optimal range (0.45% to 0.9%), significantly improving the soil's hydraulic properties (Silva et al., 2015). Additionally, SP80M ensures appropriate levels of magnesium (Mg) (maximum level: 0.33%), which are crucial for coffee development, metabolism, and vegetative vigor, particularly for the Catuaí cultivar (da Silva et al., 2014). Moreover, phosphorus (P) levels (ranging from 0.01% to 0.13% up to 0.70 m depth) are effectively maintained within the optimal range, which is essential for coffee plant growth and associated with high yields (Dias et al., 2015) throughout the soil profile due to the mixture's incorporation.

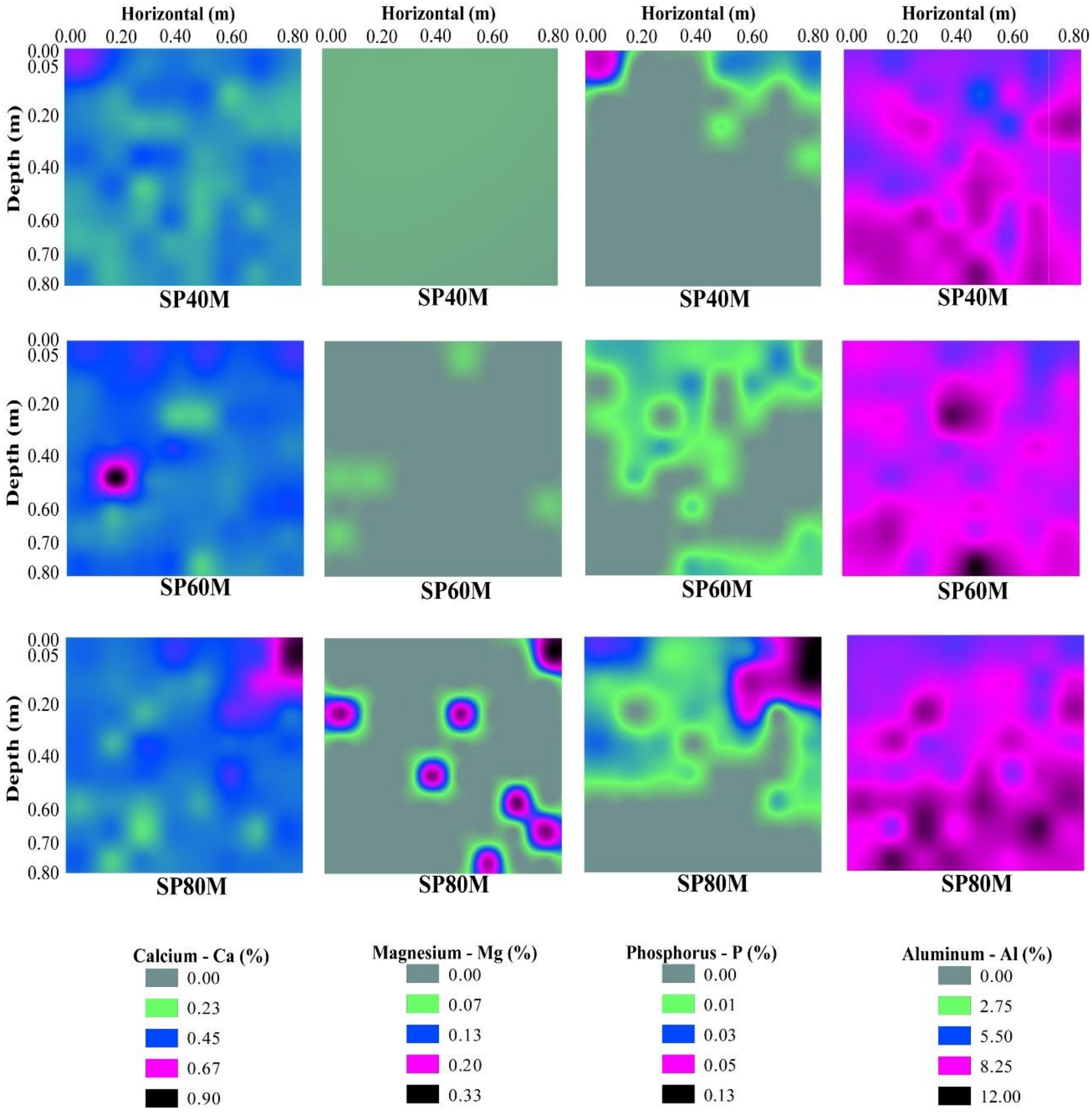


Figure 11. Maps of spatial variability of the elementary content with data provided by pXRF analysis of samples collected in the Cambisol profile (0.10 × 0.10 m grid) to characterize all management systems studied in terms of Ca (%); Mg (%), P (%) and Al (%). SP40M:

planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler.

According to Teixeira et al. (2018), preparing Cambisols up to a depth of 0.20 m in coffee areas leads to significant fertility improvements compared to the native soil, which naturally lacks adequate Ca, Mg, and P levels. Cambisols possess distinct chemical and physical characteristics (Silva et al., 2018). If these characteristics are not properly managed, this soil type may not be suitable for coffee production (Barbosa et al., 2020; Silva et al., 2021). High soil acidity in this class of soil has been highlighted by Teixeira et al. (2018). Therefore, creating suitable chemical conditions for optimal coffee establishment is essential (Barbosa et al., 2020). The subsoiler preparation at a depth of 0.80 m improved the availability of Ca, Mg, and P while reducing aluminum (Al) levels, resulting in enhanced root growth (Figure 5), improved aggregation (Figure 4E), and beneficial adjustments in structural quality (Figures 6, 10, and 8), as previously mentioned. As a perennial crop with high productivity, coffee cultivation requires significant labor, resources, and an intensive cultivation system in tropical agriculture (Carducci et al., 2017). These efforts enhance Cambisols' root environment and resource dynamics (Silva et al., 2021).

3.6. Soil and plant measurements correlations

The correlation matrix depicted in Figure 12 reveals that the reduction of void space and inter-aggregates caused by the subsoiler did not have a detrimental effect on the structural properties of the Cambisol at depths of 0.20 m and 0.70 m. This condition is evident from the negative correlations observed between stem diameter (SD) and normalized difference vegetation index (NDVI). However, there was a significant positive correlation between the coffee plant's NDVI and the presence of macrovoids, indicating that the loss of microvoids was compensated by the favorable development of larger voids, ultimately improving coffee vigor. The depth of 0.20 m emerged as the most influential in describing various factors, including PR, root system, and Al content. The SP40M, characterized by the highest PR values (Figure 6), resulted in decreased coffee plant height (PL) and NDVI, demonstrating a negative correlation (Figure 12).

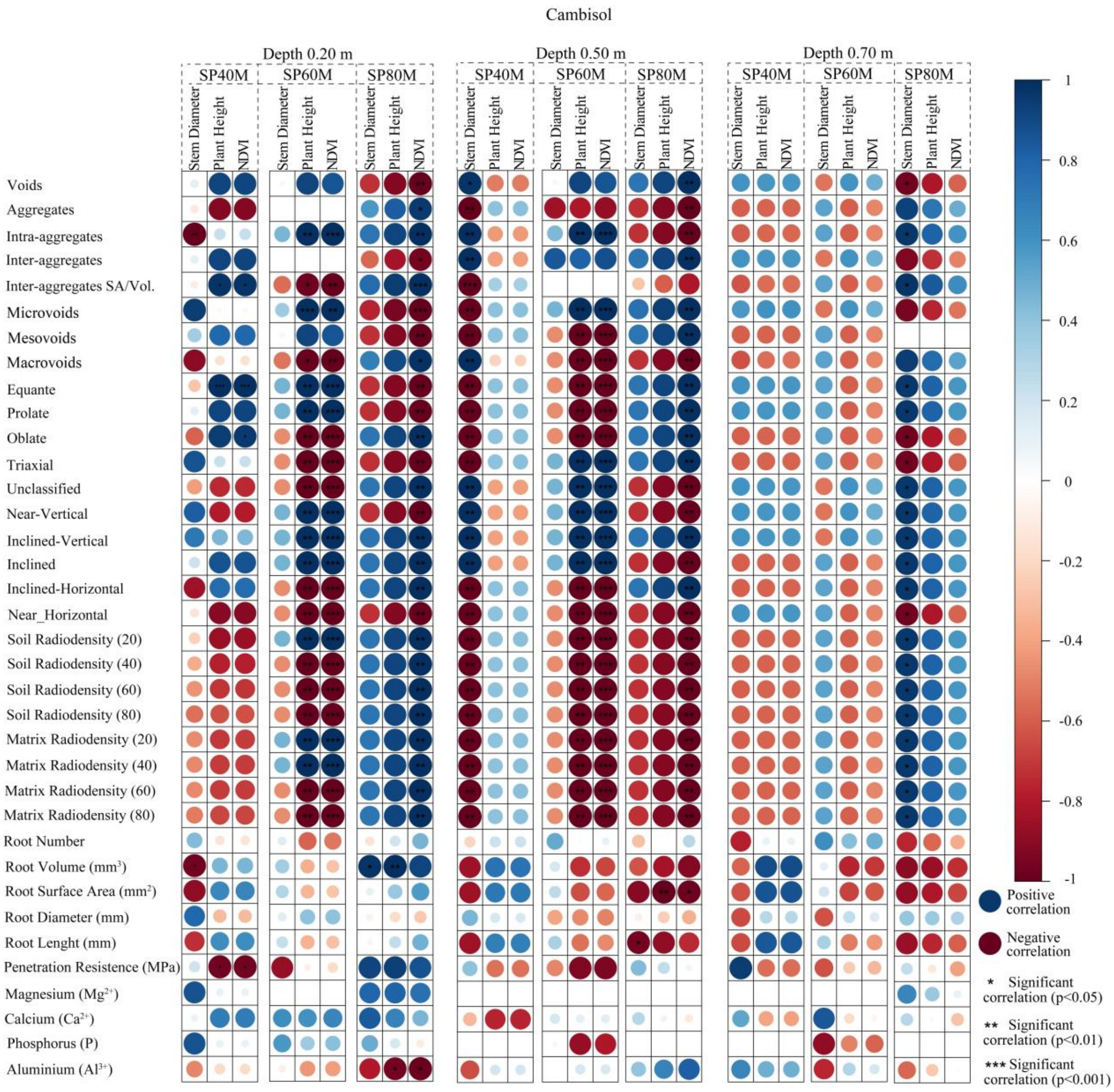


Figure 12. Correlations to X-ray microtomography soil parameters; root system; penetration resistance and elementary content with coffee plant measurements responses under different managements and depths. SP40M: planting furrow at 0.40 m with conventional fertilization and a mixture of gypsum, serpentinite, and natural phosphate using a furrower; SP60M: planting furrow at 0.60 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using a soil homogenizer; SP80M: planting furrow at 0.60 m and at 0.80 m with conventional fertilization and with a mixture of gypsum, serpentinite, and natural phosphate using both soil homogenizer and subsoiler.

In contrast, SP80M exhibited the greatest SD and PL (positive correlation) due to its larger RV (Figure 5) and improved NDVI, attributed to the lower Al content (Figure 11), showing a negative correlation (Figure 12). Interestingly, soil and matrix radiodensity, independent of proportional frequency, distinguished tomographic parameters among the soil preparations. The positive correlation between NDVI at 0.20 m and SD at 0.70 m (Figure 12) indicates the beneficial effect of SP80M. The impact of the rotary hoe tiller at 0.50 m reduced soil and matrix radiodensity, irrespective of proportionate frequency (Figure 3), resulting in improved plant height and NDVI (negative correlation). However, this outcome was not observed when combining the soil homogenizer and subsoiler. It demonstrates that the increase in density associated with SP80M at a depth of 0.50 m adversely affects coffee plant growth (negative correlation, Figure 12).

Increasing stem diameter is crucial as it indicates water deficit conditions, particularly in coffee plants (Ehrenbergerová et al., 2021). The reduction in stem diameter is directly linked to a decrease in temperature (Partelli et al., 2013), while the coffee plant's diameter and height tend to increase during the rainy season (Barros et al., 1997). NDVI is significantly correlated with water conditions, and deep soil preparation is vital in improving soil moisture in the root zone (Santos et al., 2014). Improving water conditions is particularly important for Cambisols, where deep preparation has been found to enhance coffee plant development in height and vigor by promoting root growth (Barbosa et al., 2020; Silva et al., 2021). The contributions of SP80M are directly related to its effective promotion of root exploration and its associated benefits. Root systems significantly impact soil modification, particularly regarding pore changes (Carducci et al., 2015). Long-term assessments of coffee management systems have shown improvements in soil structure, including densified layers and root growth, even in mechanical disturbances caused by subsoiling at a depth of 0.60 m (Carducci et al., 2017).

4. Conclusions

Six years after establishing the coffee plantation, the structure of Cambisol samples was analyzed using X-Ray Computed Tomography, which was allowed to assess the impact of different deep tillage strategies. Qualitative data from 3D visual images revealed that the tillage practices (furrower, soil homogenizer, and subsoiler) at their respective depths (0.20, 0.50, and 0.70 m) resulted in modifications to the soil structure. Contrary to expectations, subsoiler preparation did not reduce density at 0.70 m depth. However, our results showed that subsoiling positively influenced the structural characteristics of Cambisol by increasing density and decreasing the morphometry of voids, such as void space and inter-aggregates. This condition improved water availability and aggregate stability due to increased morphometry of voids, including intra-aggregate voids, aggregate volume, and inter-aggregate voids surface area. These modifications facilitated the expansion of the root system, resulting in lower water storage but greater accessibility to water for plants at a depth of 0.90 m, specifically for SP80M. In addition, the subsoiler enhanced mesovoids and macrovoids while reducing microvoids, thus improving porosity and size distribution along the Cambisol profile. Vertical and inclined void orientations and lower penetration resistance observed in the Dreno preparation indicated good porosity without signs of aggressive tillage or compaction. The advantages of SP80M (soil homogenizer at 0.50 m, followed by the subsoiler at 0.70 m) can be attributed to the improved incorporation and distribution of elemental content (Ca, Mg, and P) for correcting Al through a chemical amendment by the mixture at depth. Despite using identical amounts of gypsum, serpentinite, and natural phosphate in each preparation, only SP80M achieved a better concentration of these elements, optimizing Al correction along the soil profile. The changes in Cambisol structure, supported by tomographic parameters, promoted the growth of coffee plants in terms of stem diameter, height, and vegetative vigor. It was determined that deep tillage with subsoilers allied with chemical amendments effectively modified shallow and naturally dense soils.

5. References

Ajayi, A.E., Dias Junior, M.D.S., Curi, N., Araujo Junior, C.F., Aladenola, O.O., Teixeira Souza, T.T., Inda Junior, A.V., 2009. Comparison of estimation methods of soil strength in five soils. Rev. Bras. Ciênc. Solo, 33, 487–495. https://doi.org/10.1590/S0100-06832009000300002.

Alaoui, A., Goetz, B., 2008. Dye tracer and infiltration experiments to investigate macropore flow. Geoderma, 144(1-2), 279-286. https://doi.org/10.1016/j.geoderma.2007.11.020

Aluko, O., Koolen, A., 2001. Dynamics and characteristics of pore space changes during the crumbling on drying of structured agricultural soils. Soil Tillage Res. 58, 45–54. https://doi.org/10.1016/S0167-1987(00)00176-8.

Arasan, S., Akbulut, S., Hasiloglu, A.S. 2011. Effect of particle size and shape on the grain-size distribution using Image analysis. Int. J. Civ. Eng. 1, 968–985. https://10.6088/ijcser.00202010083.

Arthur, E., Tuller, M., Moldrup, P., Resurreccion, A.C., Meding, M.S., Kawamoto, K., Komatsu, T., de Jonge, L.W., 2013. Soil specific surface area and non-singularity of soil-water retention at low saturations. Soil Sci. Soc. Am. J. 77, 43–53. https://doi.org/10.2136/sssaj2012.0262.

Barbosa, S.M., Oliveira, G.C.de., Silva, B.M., Benevenute, P.A.N., Silva, R.F.DA., Curi, N., Moretti, B.DA.S., Silva, S.H.G., Norton, L.D., Pereira, V.M., 2020. Deep furrow and additional liming for coffee cultivation under first year in a naturaly dense inceptisol. Geoderma. 357, 113934. https://doi.org/10.1016/j.geoderma.2019.113934.

Barros, R.S., da S.e Mota, J.W., Da Matta, F.M., Maestri, M., 1997. Decline of vegetative growth in *Coffea arabica* L. in relation to leaf temperature, water potential and stomatal conductance. Field Crops Res. 54, 65–72. https://doi.org/10.1016/S0378-4290(97)00045-2.

Bhandari, A., Kumar, A., Singh, G., 2012. Feature Extraction using Normalized Difference Vegetation Index (NDVI): A Case Study of Jabalpur City. Proc. Technol. 6, 612–621. https://doi.org/10.1016/j.protcy.2012.10.074.

Borges, J.A., Pires, L.F., Cássaro, F.A., Auler, A.C., Rosa, J.A., Heck, R.J., Roque, W.L., 2019. X-ray computed tomography for assessing the effect of tillage systems on topsoil morphological attributes. Soil Tillage Res. 189, 25–35. https://doi.org/10.1016/j.still.2018.12.019.

Botta, G.F., Tolon-Becerra, A., Lastra-Bravo, X., Tourn, M., 2010. Tillage and traffic effects (planters and tractors) on soil compaction and soybean (*Glycine max* L.) yields in Argentinean pampas. Soil Tillage Res. 110, 167–174. https://doi.org/10.1016/j.still.2010.07.001

Brewer, R., 1976. Fabric and mineral analysis of soils. Robert E. Krieger Pub. Co., Huntington, New York. 73p.

Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., Tursina, T., 1985. Handbook for soil thin section description. Albrington: Waine Research. 152p.

Campos-Cascaredo, A., Cruz-Huerta, L., Rocha-Ortiz, S., 2021. Fine root density across soil profiles in tropical mountain cloud forest and adjacent managed fields in Vera Cruz (Mexico): Influence of soil properties. Trop. Subtrop. Agroecosystems. 24, 1870–0462. http://dx.doi.org/10.56369/tsaes.3647.

Carducci, C.E., Oliveira, G.C., Curi, N., Heck, R.J., Rossoni, D.F., 2014a. Scaling of pores in 3D images of Latosols (Oxisols) with contrasting mineralogy under a conservation management system. Soil Res. 52, 231–243. https://doi.org/10.1071/SR13238.

Carducci, C.E., Oliveira, G.C., Curi, N., Rossoni, D.F., Costa, A.L., Heck, R.J. 2014b. Spatial variability of pores in oxidic latosol under a conservation management system with different gypsium doses. Ciênc. Agrotec. 38, 445–460. https://doi.org/10.1590/S1413-70542014000500004.

Carducci, C.E., Oliveira, G.C., Curi, N., Heck, R.J., Rossoni, D.F.F., Carvalho, T.S.S., Costa, L.L., 2015. Gypsum effects on the spatial distribution of coffee roots and the pores system in oxidic Brazilian Latosol. Soil Tillage Res. 145, 171–180. https://doi.org/10.1016/j.still.2014.09.015.

Carducci, C.E., Oliveira, G.C., Zeviani, W.M., Laureano, H.A., Barbosa, S.M., Severiano, E.C., Curi, N., 2021. Preconsolidation stress of gibbsitic and kaolinitic Oxisols under a multipractice conservationist coffee system. Semin. Cienc. Agrar. 42, 1049–1068. https://doi.org/10.5433/1679-0359.2021v42n3p1049.

Carducci, C.E., Pinto, L.C., Barbosa, S.M., Costa, J.C., Zinn, Y.L., Heck, R. J., 2022. Micromorfologia e tomografia de raios-x: porosidade de um Latossolo gibbsítico sob sistema multi-práticas de manejo cafeeiro. Recima21-Revista Científica Multidisciplinar. 3, e361520–e361520. https://doi.org/10.47820/recima21.v3i6.1520.

Carducci, C.E., Vitorino, A.C.T., Serafim, M.E., Silva E.A., 2016. Aggregates morphometry in a Latosol (Oxisol) under different soil management systems. Semin. Cienc. Agrar. 37, 33–42. https://doi.org/10.5433/1679-0359.2016v37n1p33.

Carducci, C.E., Zinn, Y.L., Rossoni, D.F., Heck, R.J., Oliveira, G.C., 2017. Visual analysis and X-ray computed tomography for assessing the spatial variability of soil structure in a cultivated Oxisol, Soil Tillage Res. 173, 15–23. https://doi.org/10.1016/j.still.2016.03.006.

Carvalho, J.M., Cremon, C., Mapeli, N.C., Nunes, M.C.M., Silva, W.M., Magalhães, W.A., Santos, A.S., 2010. Análise micromorfométrica de agregados de um Latossolo Vermelho distroférrico sob diferentes sistemas de cultivo. Agrarian. 3, 275–285. https://ojs.ufgd.edu.br/index.php/agrarian/article/view/1114.

Conab, Companhia Nacional de Abastecimento. Acompanhamento da safra brasileira, café, safra 2022, 4º levantamento, dezembro de 2022. 9, 1–53. https://www.conab.gov.br/info-agro/safras/cafe (accessed 10 January 2023).

Costa, L.F., Antonino, A.C.D.B., Heck, R.J., Coutinho, A.P., Vasconcelos, T.C., Machado, C.B., 2018. X-ray computed microtomography in the evaluation of the porous system of soils. Rev. Bras. Eng. Agric. Ambient. 22, 249–254. https://doi.org/10.1590/1807-1929/agriambi.v22n4p249-254.

Costa, L.F., Antonino, A.C. D., Heck, R.J., Coutinho, A.P, Pimentel, R.M.M., Sales, F. J.R., Machado, C.B., Vasconcelos, T.C., Duarte, D.A., 2016a. Microtomografia computadorizada de raios-X na caracterização morfométrica dos poros de Neossolo Regolítico Eutrofico. J. Environ. Anal. Prog. 1, 24–33. https://doi.org/10.24221/jeap.1.1.2016.983.24-33.

Costa, L.F., Antonino, A.C.D., Heck, R.J., Coutinho, A.P, Pimentel, R.M.M., Vasconcelos, T.C., Machado, C.B., 2016b. Espaço poroso em solos brasileiros usando tomografia computadorizada de raios-X. (Porous space in Brazilian soils using X-ray computed tomography). Revista Brasileira de Geografia Física. 9, 692–706. www.ufpe.br/rbgfe.

Dalmago, G.A., Bergamaschi, H., Bergonci, J.I., Krüger, C.A.M.B., Comiran, F., Heckler, B.M.M., 2009. Retenção e disponibilidade de água às plantas, em solo sob plantio direto e preparo convencional. Rev. Bras. Eng. Agric. Ambient. 13, 855–864. https://doi.org/10.1590/S1415-43662009000700007.

Dhaliwal, J.K., Kumar, S., 2022. 3D-visualization and quantification of soil porous structure using X-ray micro-tomography scanning under native pasture and crop-livestock systems. Soil Tillage Res. 218, 105305. https://doi.org/10.1016/j.still.2021.105305.

Dias, K.G.D.L., Neto, A.E.F., Guimarães, P.T.G., Reis, T.H.P., Oliveira, C.H.C.D., 2015. Coffee yield and phosphate nutrition provided to plants by various phosphorus sources and levels. Cienc. e Agrotecnologia. 39, 110–120. https://doi.org/10.1590/S1413-70542015000200002.

Dowuona, G.N., Taina, I.A., Heck, R.J., 2009. Porosity analysis of two Acrisols by X-ray computed microtomography. Soil Sci. 174, 583–593. https://doi.org/10.1097/SS.0b013e3181c2a90b.

Ehrenbergerová, L., Klimková, M., Cano, Y.G., Habrová, H., Lvončík, S., Volařík, D., Khum, W., Němec, P., Kim, S., Jelínek, P., Maděra, P., 2021. Does Shade Impact Coffee Yield, Tree Trunk, and Soil Moisture on *Coffea canephora* Plantations in Mondulkiri, Cambodia? Sustainability, 13, 13823. https://doi.org/10.3390/su132413823.

Elliott, E.T., Coleman, D.C., 1988. Let the soil work for us. Ecol. Bull., 39: 23–32.

Guimarães, P.T.G., Garcia, A.W.R., Alvarez V.V.H., Prezotti, L.C., Viana, A.S., Miguel, A.E., Oliveira, J.D., 1999. Cafeeiro. CFSMG - Comissão de Fertilidade do Solo do Estado de Minas Gerais. Recomendação para o uso de corretivos e fertilizantes em Minas Gerais, 5ª aproximação. Viçosa.

Horta, I.M.F., Pereira, J.A.A, Marques, J.J., Carvalho, L.M.T., 2009. Levantamento de reconhecimento com apoio digital dos solos do município de Nazareno-MG. Cienc. e Agrotecnologia. 33, 940–1947. https://doi.org/10.1590/S1413-70542009000700042.

Hou, L., Gao, W., der Bom, F., Weng, Z., Doolette, C. L., Maksimenko, A., Hausermann, D., Zheng, Y., Tang, C., Lombi, E., Kopittke, P. M., 2022. Use of X-ray tomography for examining root architecture in soils. Geoderma. 405, 115405. https://doi.org/10.1016/j.geoderma.2021.115405.

Houston, A., Otten, W., Falconer, R., Monga, O., Baveye, P., Hapca, S., 2017. Quantification of the pore size distribution of soils: Assessment of existing software using tomographic and synthetic 3D images. Geoderma. 299, 73–82. https://doi.org/10.1016/j.geoderma.2017.03.025.

Jassogne, L., McNeill, A., Chittleborough, D., 2007. 3D-visualization and analysis of macro- and meso-porosity of the upper horizons of a sodic, texture-contrast soil. Eur. J. Soil Sci. 58, 589–598. https://doi.org/10.1111/j.1365-2389.2006.00849.x.

Jesus, A.M.S., de Carvalho, S.P., Soares, Â.M., 2006. Comparação entre sistemas radiculares de mudas de *Coffea arabica* L. obtidas por estaquia e por sementes. Coffee Science. 1, 14-20. http://www.coffeescience.ufla.br/index.php/Coffeescience/article/view/13. Acesso em: 24 jul.

2023.

Jefferies, D.A., Heck, R.J., Thevathasan, N.V., Gordon, A.M., 2014. Characterizing soil surface structure in a temperate tree-based intercropping system using X-ray computed tomography._Agrofor. Syst. 88, 645–656. https://doi.org/10.1007/s10457-014-9699-0.

Jorge, L.A.C., Silva, D.J.C.B., 2010. SAFIRA: Manual de utilização. São Carlos: Embrapa CPDIA, 29p. Available in: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/884593/safira-manual-de-utilizacao.

Karthika, K.S., Anil Kumar K.S., Nair K. M., Violet M. D'Souza, Nagaraj J. S., Lalitha M., Arti Koyal, Jayaramiah M., Parvathy S., Sujatha K., Shivanand K., Ramamurthy V., Srinivas S., Raghuramulu Y., Hegde R. and Singh S. K., 2020. Sustainability of coffee land use upon conversion from natural forest in Western Ghats of South India: An evaluation. Soil Use and Management. 38:873–889. https://doi.org/10.1111/sum.12692.

Köppen, W. Das geographisca System der Klimate. Gebr, Borntraeger, 1936. p.1–44.

Lee, S., Wolberg, G., Shin, S.Y., 1997. Scattered data interpolation with multilevel B-splines. IEEE Trans. Vis. Comput. Graph. 3, 228–244. https://doi.org/10.1109/2945.620490.

Lima, V.M.P., Magalhães, C.A.D.S., Oliveira, G.C., Lima, J.M.D., 2010. Structural quality of soils cultivated with coffee and pasture in an environmental protection area. Rev. Bras. Cienc. Solo. 34, 709–716. https://doi.org/10.1590/S0100-06832010000300012.

Lima, V.M.P., Oliveira, G.C., Serafim, M.E., Curi, N., Evangelista, A.R., 2012. Intervalo Hídrico Ótimo como Indicador de melhoria da Qualidade Estrutural de Latossolo Degradado. Rev. Bras. Cienc. Solo. 36, p.71–78. https://doi.org/10.1590/S0100-06832012000100008.

Maja, M.M., Ayano, S.F., 2021. The Impact of Population Growth on Natural Resources and Farmers' Capacity to Adapt to Climate Change in Low-Income Countries. Environ. Earth Sci. 5, 271–283. https://doi.org/10.1007/s41748-021-00209-6.

Medeiros, J.C., Figueiredo, G.C., Mafra, Á.L., Rosa, J.D., Yoon, S.W., 2013. Deep subsoiling of a subsurface-compacted typical hapludult under citrus orchard. Rev. Bras. Cienc. Solo. 37, 911–919. https://doi.org/10.1590/S0100-06832013000400008.

Ng, C.W.W., Ni, J.J., Leung, A.K., Wang, Z.J., 2016. A new and simple water retention model for root-permeated soils. Geotech. Lett. 6, 106–111. https://doi.org/10.1680/jgele.15.00187.

Nunes, M.R., Karlen, D.L., Moorman, T.B., 2020. Tillage Intensity Effects on Soil Structure Indicators—A US Meta-Analysis. Sustainability. 12, 2071. https://doi.org/10.3390/su12052071.

Oliveira, J., Appoloni, C., Coimbra, M., Reichardt, K., Bacchi, O., Ferraz, E., Silva, S., Galvão Filho, W., 1998. Soil structure evaluated by gamma-ray attenuation. Soil Tillage Res. 48, 127–133. https://doi.org/10.1016/S0167-1987(98)00130-5.

Othmer, H., Diekkrüger, B., Kutilek, M., 1991. Bimodal porosity and unsaturated hydraulic conductivity. Soil Sci. 152, 139-150.

Partelli, F.L., Marré, W.B., Falqueto, A.R., Vieira, H.D., Cavatti, P.C., 2013. Seasonal vegetative growth in genotypes of *Coffea canephora*, as related to climatic factors. J. Agric. Sci. 5, 108. http://dx.doi.org/10.5539/jas.v5n8p108.

Passoni, S., Pires, L.F., Heck, R.J., Rosa, J.A., 2015. Three dimensional characterization of soil macroporosity by x-ray microtomography. Rev. Bras. Cienc. Solo. 39, 448–457. https://doi.org/10.1590/01000683rbcs20140360.

Pereira, T.T.C., Ker, J.C., Schaefer, C.E.G.R., Barros, N.F., Neves, J.C.L., Almeida, C.C., 2010. Genesis of latosols and Cambisols developed from pelitic rocks of the Bambui group, Minas Gerais state – Brazil. Rev. Bra. Ciên. Solo 34, 1283–1296. https://doi.org/10.1590/S0100-06832010000400026.

Pierret, A., Latchackak, K., Chathanvongsa, P., Sengtaheuanghoung, O., Valentin, C., 2007. Interactions between root growth, slope and soil detachment depending on land use: a case study in a small mountain catchment of Northern Laos. Plant and Soil. 301, 51-64. https://doi.org/10.1007/s11104-007-9413-3

Pires, L.F., Auler, A.C., Roque, W.L., Mooney, S.J., 2020. X-ray microtomography analysis of soil pore structure dynamics under wetting and drying cycles. Geoderma. 362, 114103. https://doi.org/10.1016/j.geoderma.2019.114103.

Pires, L.F., Borges, J.A.R., Rosa, J.A., Cooper, M., Heck, R.J., Passoni, S., Roque, W.L., 2017. Soil structure changes induced by tillage systems. Soil Tillage Res. 165, 66–79. https://doi.org/10.1016/j.still.2016.07.010.

Pires, L.F., Mooney, S.J., Auler, A.C., Atkinson, B., Sturrock, C.J., 2019a. X-ray microtomography to evaluate the efficacy of paraffin wax coating for soil bulk density evaluation. Geoderma. 337, 935–944. https://doi.org/10.1016/j.geoderma.2018.11.017.

Pires, L.F., Roque, W.L., Rosa, J.A., Mooney, S.J., 2019b. 3D analysis of the soil porous architecture under long term contrasting management systems by X-ray computed tomography. Soil Tillage Res. 191, 197–206. https://doi.org/10.1016/j.still.2019.02.018.

QGIS Development Team, 2021. QGIS Geographic Information System. Open Source Geospatial Foundation. https://qgis.org/en/site/.

R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.J., 2018. Soil structure as an indicator of soil functions: a review. Geoderma. 314, 122–137. http://dx.doi.org/10.1016/j.geoderma.2017.11.009.

Reynolds, W.D., Drury, C.F., Tan, C.S., Fox, C., Yang, X.M., 2009. Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma. 152, 252–263. https://doi.org/10.1016/j.geoderma.2009.06.009.

Saffari, N., Hajabbasi, M.A., Shirani, H., Mosaddeghi, M.R., Owens, G., 2021. Influence of corn residue biochar on water retention and penetration resistance in a calcareous sandy loam soil. Geoderma. 383, 114734. https://doi.org/10.1016/j.geoderma.2020.114734.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Araújo Filho, J.C., Oliveira, J.B., Cunha, T.J.F., 2018. Sistema brasileiro de classificação de solos. 5. ed. revisada e ampliada, Embrapa. Brasília. 356 p.

Santos, W.J.R., Silva, B.M., Oliveira, G.C., Volpato, M.M.L., Lima, J.M., Curi, N., Marques, J.J., 2014. Soil moisture in the root zone and its relation to plant vigor assessed by remote sensing at management scale. Geoderma. 221–222, 91–95. https://doi.org/10.1016/j.geoderma.2014.01.006.

Serafim, M.E., Oliveira, G.C., Curi, N., Lima, J.M., Guimarães, P.T.G., Lima, V.M.P., 2013a. Potencialidades e limitações de uso de Latossolos e Cambissolos, sob sistema conservacionista em lavouras Cafeeiras. Biosci J. 29, 1640-1652. https://seer.ufu.br/index.php/biosciencejournal/article/view/15154.

Serafim, M.E., Oliveira, G.C., Lima, J.M., Silva, B.M., Zeviani, W.M., Lima, V.M.P., 2013b. Disponibilidade hídrica e distinção de ambientes para cultivo de cafeeiros. Revista Brasileira de Engenharia Agrícola e Ambiental. Campina Grande, v.17, n.4, p.362-370. https://doi.org/10.1590/S1415-43662013000400002.

Silva, B.M., Oliveira, G.C., Serafim, M.E., Silva, E.A., Guimaraes, P.T.G., Melo, L.B.B., Norton, L.D., Curi, N., 2019. Soil moisture associated with least limiting water range, leaf water potential, initial growth and yield of coffee as affected by soil management system. Soil Tillage Res. 189, 36–43. https://doi.org/10.1016/j.still.2018.12.016.

Silva, B.M., Santos, W.J.R., Oliveira, G.C., Lima, J.M., Curi, N., Marques, J. J.G.S.M., 2015. Soil moisture space-time analysis to support improved crop management. Cienc. e Agrotecnologia, 39, 39–47. https://doi.org/10.1590/S1413-70542015000100005.

Silva, É.A., de Oliveira, G.C., Carducci, C.E., Silva, B.M., Serafim, M.E., 2016a. Aggregates morphometry of a Inceptisol under conservationist system. Semin. Agrar. 37, 1165–1176. https://doi.org/10.5433/1679-0359.2016v37n3p1165.

Silva, É.A., Oliveira, G.C., Carducci, C.E., Lima, J.M., Melo, L.B.B., Benevenute, P.A.N., 2016b. Stability of soil aggregates in Latosols and Cambisols via standard method and sonification. Afr. J. Agric. Res. 11, 38943903. https://doi.org/10.5897/AJAR2016.11192.

Silva, É.A., Silva, S.H.G., Oliveira, G.C., Carducci, C.E., 2016c. Root spatial distribution in coffee plants of different ages under conservation management system. Afr. J. Agric. Res. 11, 4970–4978. https:// doi.org/10.5897/AJAR2016.11356.

Silva, R.F., Severiano, E.C., Oliveira, G.C., Barbosa, S.M., Peixoto, D.S., Tassinari, D., Silva, B.M., Silva, S.H.G., Dias Júnior, M.S., Figueiredo, T.A.F.R., 2021. Changes in soil profile hydraulic properties and porosity as affected by deep tillage soil preparation and Brachiaria grass intercropping in a recent coffee plantation on a naturally dense Inceptisol. Soil Tillage Res. 213, 105127. https://doi.org/10.1016/j.still.2021.105127.

Silva, S.H.G., Hartemink, A.E., Teixeira, A.F. dos S., Inda, A.V., Guilherme, L.R.G., Curi, N., 2018. Soil weathering analysis using a portable X-ray fluorescence (PXRF) spectrometer in an Inceptisol from the Brazilian Cerrado. Appl. Clay Sci. 162, 27–37. https://doi.org/10.1016/j.clay.2018.05.028.

Silva, VA., Abrahão, J.C.d.R., Reis, A.M., Santos, M.d.O., Pereira, A.A., Botelho, C.E., Carvalho, G.R., Castro, E.M.d., Barbosa, J.P.R.A.D., Botega, G.P., Oliveira, A.C.B.d., 2022. Strategy for Selection of Drought-Tolerant Arabica Coffee Genotypes in Brazil. Agronomy. 12, 2167. https://doi.org/10.3390/agronomy12092167.

Soil Survey Staff, 2014. Keys to Soil Taxonomy, 12th ed.; USDA-NRCS: Washington, DC, USA.

Taina, I.A., Heck, R.J., Deen, W., Ma, E.Y., 2013. Quantification of freeze–thaw related structure in cultivated topsoils using X-ray computer tomography. Can. J. Soil Sci. 93 533–553. https://doi.org/10.4141/cjss2012-044.

Taina, I.A., Heck, R.J., Elliot, T., 2008. Application of X-ray computed tomography to soil science: A literature review. Can. J. Soil Sci. 88 1–18. https://doi.org/10.4141/CJSS06027.

Taina, I.A., Heck, R.J., Elliot, T.R., Scaiff, N., 2010. Micromorphological and X-ray μCT study of Orthic Humic Gleysolsunder different management conditions. Geoderma. 158, 110–

119. https://doi.org/10.1016/j.geoderma.2010.02.009.

Teixeira, A.F.D.S., Weindorf, D.C., Silva, S.H.G., Guilherme, L.R.G., Curi, N., 2018. Portable X-ray fluorescence (pXRF) spectrometry applied to the prediction of chemical attributes in Inceptisols under different land uses. Cienc. e Agrotecnologia. 42, 501–512. https://doi.org/10.1590/1413-70542018425017518.

Teixeira, P.C., Donagemma, G.K., Fontana, A., Teixeira, W.G., (2017). Manual de métodos de análise de solo, third ed. Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Brasília.

Usman, A.A., Mamman, M.B.A., 2022. Spatio-Temporal Analysis of Dry Spell for Agricultural Decision Support in North-Central Nigeria. Environmental and Earth Sciences Research Journal, 9(1), 1-7. http://iieta.org/journals/eesrj.

Wei, T., Simko, V., 2021. R package 'corrplot': Visualization of a Correlation Matrix. (Version 0.92). https://github.com/taiyun/corrplot.

Wilding, L.P., Lin, H., 2006. Advancing the frontiers of soil science towards a geoscience. Geoderma. 131, 257–274. https://doi.org/10.1016/j.geoderma.2005.03.028.

WRB, I.W.G., 2014. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Report No.106. FAO, Rome.

Xu, H., Chen, F., Yao, X., Tan, Y., 2018. Micro-scale moisture distribution and hydrologically active pores in partially saturated asphalt mixtures by X-ray computed tomography. Constr. Build. Mater. 160, 653–667. https://doi.org/10.1016/j.conbuildmat.2017.11.107.

Zhu, F., Liao, J., Xue, S., Hartley, W., Zou, Q., Wu, H., 2016. Evaluation of aggregate microstructures following natural regeneration in bauxite residue as characterized by synchrotron-based X-ray micro-computed tomography. Sci. Total Environ. 573, 155–163. https://doi.org/10.1016/j.scitotenv.2016.08.108

Zingg, T., 1935. Beitrag zur schotteranalyse (Doctoral dissertation). ETH Zurich. https://doi.org/10.3929/ethz-a-000103455.

Final Considerations

Investing in agricultural technologies for initial soil preparation, such as deep planting furrows, is crucial for successful coffee cultivation. It improves Cambisol's physical and water quality, creating favorable conditions for coffee plant development. Soil preparation up to 0.80 m with additional liming up to 0.60 m has proven beneficial in the medium and long term, improving physical quality indicators. On the other hand, a planting furrow depth of up to 0.60 m without additional liming is also advantageous, leading to better root development, water storage, and antioxidant protection, making it a cost-effective option for coffee producers under drought conditions. Furthermore, deep soil preparation at 0.80 m and appropriate chemical correction using gypsum, serpentinite, and natural phosphate effectively modified naturally dense Cambisol, enhancing physical and water conditions for coffee plant growth and establishment under rainfed conditions.

Concerning water storage, the study of soil moisture along the soil profile is influenced by various factors, such as soil attributes, management, chemical correction, and root system distribution. Therefore, new research experiments are needed to provide a more conclusive assessment of soil water movement, availability, and root absorption. In addition to mapping the physical and chemical properties of the soil, it is essential to correlate plant development variables and productivity to make decisions and propose better soil management practices, considering the timely introduction of agricultural implements. This research will ensure greater food security and guarantee economically viable and sustainable approaches in conjunction with water resource management.