EDUARDO MEDEIROS SEVERO

COVER CROP MANAGEMENT SYSTEM AND SOIL QUALITY IN RELATION TO WATER EROSION IN OLIVE ORCHARDS

LAVRAS – MG
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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, linha de pesquisa em Manejo e Conservação do Solo e da Água, para a obtenção do título de Doutor.

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EDUARDO MEDEIROS SEVERO

COVER CROP MANAGEMENT SYSTEM AND SOIL QUALITY IN RELATION TO WATER EROSION IN OLIVE ORCHARDS

SISTEMAS DE MANEJO DE COBERTURA DO SOLO E QUALIDADE DO SOLO EM RELAÇÃO À EROSÃO HÍDRICA EM POMARES DE OLIVEIRAS

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, linha de pesquisa em Manejo e Conservação do Solo e da Água, para a obtenção do título de Doutor.

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Ao meu pai, Sebastião Severo de Oliveira (in memoriam), cuja memória permanece viva em meu coração como fonte inesgotável de amor, amizade e inspiração – meu maior exemplo de vida. À minha mãe, Rosilene Alves Medeiros, pelo amor incondicional, pela humildade e pela dedicação incansável, sempre guiadas pelo sacrifício em prol daqueles que ama. À minha noiva Gabriele Medeiros Hermógenes, pelo apoio inabalável, por ser minha fortaleza e meu ponto de equilíbrio em todos os momentos. Com gratidão, dedico.

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Muito obrigado!

"... Não há posses valiosas que não necessite de ser conquistada e reconquistada...
– Eu enumerei algumas coisas sobre os quais acredito que possamos construir nosso futuro...
...Eu gosto de chamá-las as coisas invisíveis da vida; as coisas que nossas mães nos ensinam desde a primeira vez que estivemos no colo delas – honestidade, integridade, verdade, beleza, liberdade, bondade, pureza, amor a Deus, amor ao lar e amor ao País. Vocês não podem pegar uma dessas virtudes e esconder dos olhos dos homens e mulheres. Elas são de graça para qualquer um que as aceite. São as âncoras as quais devemos nos atar se quisermos levar vidas belas e justas."

(Frank Sherman Land,

in: Duncan, H. E. Hi Dad! Kansas City: DeMolay International, 1970).

RESUMO

A qualidade do solo desempenha um papel crucial no equilíbrio e na produtividade agroecossistemas, além de influenciar o ambiente circundante. No entanto, sua definição e quantificação apresentaram desafios consideráveis. Para garantir o manejo e a conservação dos solos para as gerações futuras, é necessário estabelecer uma definição abrangente de qualidade do solo que considere suas múltiplas funções. Contudo, ainda existem lacunas a serem preenchidas para avançar na avaliação da qualidade do solo, especialmente em sistemas de produção localizadas em regiões suscetíveis à rápida degradação devido à erosão hídrica, como ocorre na olivicultura em solos tropicais. O objetivo principal desta pesquisa foi avaliar a qualidade do solo e o efeito de diferentes sistemas de plantas de cobertura na mitigação da erosão hídrica em pomares de oliveira sob condições tropicais. Esta tese foi estruturada em três artigos. O primeiro artigo avaliou diferentes sistemas de manejo de plantas de cobertura e seus impactos na estrutura e microestrutura do solo, utilizando análises de campo e micromorfologia. Observou-se que o tratamento com oliveiras e feijão-de-porco, seguido pela manutenção da vegetação espontânea manejada com coroamento e roçada, minimizou as perdas de solo ao longo de seis anos, promovendo a melhoria da estrutura do solo, aumento da espessura do horizonte A e da porosidade total. Além disso, a presença de fragmentos de películas de argila iluvial destacou o papel das forças erosivas na desagregação e redistribuição de partículas finas na camada superficial. O segundo artigo investigou a relação entre resistividade elétrica e o conteúdo de água do solo em diferentes posições na paisagem, com o objetivo de avaliar o efeito do manejo de plantas de cobertura em pomares de oliveiras. O método de resistividade elétrica demonstrou ser uma ferramenta válida para estimar a quantidade e distribuição da umidade do solo em Cambissolos em regiões tropicais, permitindo a criação de modelos de calibração específicos para diferentes usos do solo, com notável precisão na estimativa do conteúdo de água. As avaliações de resistividade elétrica possibilitaram associar variações na resistividade (ρ) – ou no conteúdo de água inferido (θ) – com a adoção de distintos sistemas de manejo da conservação do solo, proporcionando uma interpretação dos processos complexos no sistema solo-planta. O terceiro artigo avaliou a qualidade do solo para cada uso específico. Os principais achados indicaram que as perdas de solo e água estavam negativamente correlacionadas aos índices de qualidade do solo. Os sistemas de manejo com plantas de cobertura demonstraram melhorias significativas na qualidade do solo e na redução da erosão hídrica, com a vegetação espontânea apresentando os melhores resultados. Observou-se também que a oliveira cultivada em solo descoberto está altamente susceptível à degradação ambiental ao longo dos anos. Finalmente, conclui-se que o manejo das plantas de cobertura exige um equilíbrio cuidadoso com o crescimento das plantações de oliveiras para maximizar seus benefícios.

Palavras-chave: morfologia do solo; resistividade elétrica; *Olea europaea* L.

ABSTRACT

Soil quality plays a crucial role in the balance and productivity of agroecosystems while influencing the surrounding environment; however, its definition and quantification present significant challenges. To ensure effective soil management and conservation for future generations, a comprehensive definition of soil quality must encompass its multiple functions. Gaps remain in advancing soil quality assessments, particularly in production systems prone to rapid degradation due to water erosion, such as olive cultivation on tropical soils. This research aimed to evaluate soil quality and the effects of different cover crop systems in mitigating water erosion in tropical olive orchards. The first study assessed cover crop management effects on soil structure and microstructure using field analysis and micromorphology, revealing that the combination of olive trees with jack beans, followed by crowned and mown spontaneous vegetation, minimised soil loss over six years while improving soil structure, increasing A horizon thickness, and enhancing total porosity. The presence of illuvial clay film fragments highlighted the role of erosive forces in the detachment and redistribution of fine soil particles within the surface layer. The second study examined the relationship between electrical resistivity and soil water content across different landscape positions, demonstrating that electrical resistivity is a reliable tool for estimating soil moisture distribution in Inceptisols under tropical conditions. Specific calibration models for different land uses were developed with remarkable precision, allowing for the association of variations in resistivity (ρ) – or inferred water content (θ) – with distinct soil conservation management systems and their impact on the soil-plant system. The third study evaluated soil quality under different land uses, revealing a negative correlation between soil and water losses and soil quality indices. Cover crop management significantly improved soil quality and reduced water erosion, with spontaneous vegetation yielding the most favourable results, while olive trees on bare soil were highly susceptible to environmental degradation. Overall, the findings highlight the need for careful integration of cover crop management with olive tree growth to maximise soil conservation benefits.

Keywords: electrical resistivity; *Olea europaea* L.; soil morphology.

INDICADORES DE IMPACTO

A pesquisa gera impactos significativos em diversas áreas ao integrar sustentabilidade, inovação e conservação do solo. No âmbito social, a melhoria da qualidade do solo e a redução da erosão promovem maior produtividade agrícola, beneficiando comunidades rurais que dependem da agricultura para subsistência e geração de renda. Além disso, práticas sustentáveis de manejo do solo reduzem custos com insumos e minimizam impactos ambientais, contribuindo para o bem-estar rural. A disseminação de técnicas eficazes fortalece a capacitação e a conscientização ambiental, incentivando a adoção de práticas conservacionistas. No campo tecnológico, a aplicação da resistividade elétrica como ferramenta de monitoramento da umidade do solo representa um avanço para a agricultura de precisão, permitindo um manejo agrícola mais eficiente e sustentável, além de possibilitar a integração de tecnologias na conservação do solo. Os impactos econômicos incluem a redução de custos agrícolas por meio da adoção de plantas de cobertura, que diminuem a necessidade de fertilizantes e corretivos do solo, além do aumento da produtividade devido à melhoria da estrutura do solo e da retenção de água. A valorização da terra também é um benefício, pois solos bem manejados possuem maior potencial produtivo e atraem investimentos de longo prazo. No campo cultural, a pesquisa resgata e valoriza conhecimentos tradicionais sobre o manejo do solo, promovendo uma abordagem integrada entre práticas ancestrais e tecnologia moderna. Também fomenta uma mudança de mentalidade no setor agrícola, incentivando a transição para sistemas conservacionistas e agroecológicos, mais resilientes às mudanças climáticas. Dessa forma, a pesquisa contribui diretamente para os Objetivos de Desenvolvimento Sustentável (ODS), especialmente para o ODS 2 – Fome Zero e Agricultura Sustentável – ao garantir maior produtividade e segurança alimentar; ODS 6 – Água Potável e Saneamento – ao promover a conservação da umidade do solo e a gestão eficiente dos recursos hídricos; ODS 13 – Ação Contra a Mudança Global do Clima – ao fortalecer a resiliência dos agroecossistemas e mitigar a degradação ambiental; e ODS 15 – Vida Terrestre – ao incentivar a conservação do solo e da biodiversidade. Assim, os resultados do estudo promovem benefícios de longo prazo para a sociedade, a economia e o meio ambiente.

IMPACT INDICATORS

The research generates significant impacts across multiple areas by integrating sustainability, innovation, and soil conservation. In the social sphere, improvements in soil quality and erosion reduction enhance agricultural productivity, benefiting rural communities that rely on farming for subsistence and income generation. Additionally, sustainable soil management practices reduce input costs and minimise environmental impacts, contributing to rural well-being. The dissemination of effective techniques strengthens capacity building and environmental awareness, encouraging the adoption of conservation practices. In the technological field, the application of electrical resistivity as a soil moisture monitoring tool represents an advancement in precision agriculture, enabling more efficient and sustainable land management while integrating technologies for soil conservation. The economic impacts include cost reductions in agriculture through the adoption of cover crops, which decrease the need for fertilisers and soil amendments, as well as increased productivity due to improved soil structure and water retention. Land valuation is another benefit, as well-managed soils have greater productive potential and attract long-term investments. In the cultural domain, the research rescues and values traditional knowledge on soil management, fostering an integrated approach that combines ancestral practices with modern technology. It also promotes a shift in mindset within the agricultural sector, encouraging the transition to conservationist and agroecological systems that are more resilient to climate change. Consequently, the research directly contributes to the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 – Zero Hunger and Sustainable Agriculture – by ensuring greater productivity and food security; SDG 6 – Clean Water and Sanitation – by promoting soil moisture conservation and efficient water resource management; SDG 13 – Climate Action – by enhancing agroecosystem resilience and mitigating environmental degradation; and SDG 15 – Life on Land – by fostering soil and biodiversity conservation. Thus, the study’s findings generate long-term benefits for society, the economy, and the environment.

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FIRST PART

GENERAL PRESENTATION

The olive tree (*Olea europaea* L.) is a temperature fruit tree of the *Oleaceae* family, native to the Mediterranean region and introduced to Brazil by European immigrants during colonization (WREGE et al., 2015). It produces fruits that can be eaten or processed into olive oil, which is highly valued for its quality in the global market. Although olive cultivation has expanded in Brazil, national production remains relatively low (ALVARENGA et al., 2017). Despite the country's high temperatures, certain regions offer favorable conditions for olive tree development due to their climate and topography, particularly in the south of Minas Gerais (APARECIDO et al., 2023; SILVA et al., 2012).

One of the reasons for the low production is the loss of soil and water due to erosion processes. In Brazil, olive cultivation is often concentrated in high-altitude areas with rugged terrain, which are characterized by shallow soils, high erosion rates, and limited *solum* thickness. These include Cambissolos (Inceptisols), Neossolos Litólicos (Entisols) and Argissolos (Ultisols) (BENITES et al., 2003; SILVA et al., 2019; OLIVEIRA et al., 2024). Additionally, olive plants have a small canopy and low leaf cover when young, requiring wide spacing, which increases soil exposure. This lack of soil cover heightens the risk of water erosion, compromising soil quality (BENIAICH et al., 2019).

The majority of arable high-altitude soils in tropical climates belong to the Inceptisols order, which have a high silt content, blocky structure, low permeability, small *solum* thickness, are associated with steep slopes and, if not protected by vegetation cover, soil losses are unsustainable, reaching values of up to 111-175 Mg ha^{-1} $year^{-1}$ (SCHICK et al., 2000; SILVA et al., 2009). Studies on these soils with olive cultivation in tropical conditions, in the absence of soil cover, showed soil and water losses ranging from 268-279 Mg ha^{-1} $year^{-1}$ to 386-568 mm $year^{-1}$, respectively (BENIAICH et al., 2023).

Soil is a resource that takes many years to recover if not properly managed, so there is growing concern about its sustainable use in agriculture to avoid soil and water losses (BENIAICH et al., 2020). Water erosion reduces soil fertility and affects carbon dynamics. For this reason, conservation agriculture seeks to mitigate erosion by using practices such as cover crop management and/or the use of spontaneous plants to reduce soil and water losses (OLIVEIRA et al., 2024). In addition, sustainable soil management systems play a fundamental role in improving and/or maintaining soil carbon stocks, improving CO_2 sequestration from the atmosphere, preventing erosion and nutrient losses, increasing

biodiversity and ecosystem stability (CELANO et al., 2011; GUIMARÃES et al., 2021) and soil quality.

Soil quality influences the balance and productivity of an ecosystem and its surrounding environment; however, defining and quantifying this aspect has proven to be a challenging task. In order to manage and conserve soils for future generations, their quality must be defined to encompass multiple soil functions (CÂNDIDO et al., 2015). The broadest definition of soil quality is the ability of the soil to function to sustain animal and plant productivity, maintain or improve water and air quality, and provide shelter and human health (KARLEN et al., 1997).

Soil quality studies are important to provide an up-to-date diagnosis of the soil by analyzing certain soil properties (SANTOS et al., 2021). Among the different methods for assessing soil quality, soil structure studies stand out, which are carried out by visual analysis through the morphological description of soil profiles in the field for each horizon and/or layer, and can be complemented by the evaluation of undeformed soil samples and microscopic analyses of soil micromorphology (SANTOS et al., 2015; STOOPS, 2003). Despite the tools available to study the physical behaviour of the soil in response to changes in soil use and management, the impact of these practices on the structure is still unclear, especially when it comes to micro-scale changes (CANISARES et al., 2020).

Another innovative way of assessing and monitoring soil quality is through indirect measurements using sensors. Among these, electrical resistivity sensors have been more widely used by those seeking to estimate soil moisture based on electrical properties (ACOSTA et al., 2022; MELO et al., 2021, 2023; SANTANA et al., 2023). This is justified by the fact that traditional techniques appear to be limited to assessing the rhizosphere and provide a single point of measurement, whereas electrical resistivity allows continuous measurements in spatial variations in the horizontal and vertical directions.

Similarly, a soil quality index (SQI) is one of the best methods for assessing soil quality, as it arises soil attributes in a format that facilitates understanding of soil processes and promotes proper soil management (JUHOS et al., 2019). SQIs are among the most widely used methods due to their ease of use, as they are quantitatively flexible and can be used to evaluate soil and ecosystem management (CÂNDIDO et al., 2015).

A SQI is a score that combines a variety of information about the soil, assessing its 'suitability' to perform one or more functions according to the attributes chosen, and a low suitability result in a low SQI score (ARMENISE et al., 2013). As such, SQIs have been fundamental in assessing soil quality in relation to water erosion at a local scale (CÂNDIDO

et al., 2015; SANTOS et al., 2021) and also regionally (LIMA et al., 2016). Soil physical, chemical and/or biological attributes can be used as quality indicators to measure a soil's ability to perform its essential functions for sustainable management.

Traditionally, chemical, physical and biological soil attributes have been the main indicators used to assess soil quality (CÂNDIDO et al., 2015; MARION et al., 2022), but there are now studies that add more facets to improve understanding, such as the selection of morphological attributes and soil macrofauna (VASU; TIWARY; CHANDRAN, 2024). In Brazil, the number of publications mentioning the term soil quality has increased significantly in recent years, but few studies focus on assessing soil quality in a way that includes the chemical, physical and biological indicators of the soil in an integrated manner, which means that there are still gaps to be filled in order to advance in the assessment of soil quality (SIMON et al., 2022), especially in different production systems in regions that are susceptible to rapid degradation due to water erosion, as is the case of olive production environments in tropical zones.

OBJECTIVES AND THESIS STRUCTURE

The general aim of this thesis was to assess the soil quality and the effect of different cover crop management systems to mitigate water erosion in tropical olive orchards. The specific aims were: 1) Evaluate the morphology of a Dystrudept subjected to cover crop management systems through field analysis and micromorphology; 2) To calibrate an equation for the electrical resistivity and soil water content relationship for individual soil uses in a Dystrudept; 3) Evaluate the spatial variability of soil water contents affected by cover crop management systems using electrical resistivity; 4) Identify the physical and chemical attributes that serve as indicators of soil quality concerning soil and water losses, due to water erosion, in a Dystrudept where soil cover crop management systems are employed in tropical olive tree cultivation.

To address these objectives, this thesis was structured into three papers. The first paper evaluates different cover crop management systems in soil structure and microstructure through field analysis and micromorphology. Five soil profiles were sampled for morphological description, and undisturbed soil samples were collected from the vertical face of the pit to perform the micromorphological description and interpretation of the thin sections. The second paper used the electrical resistivity and soil water content relationship with different landscapes position to evaluate the effect of cover crop management in olive orchards. Finally, the last paper evaluated the soil quality for each use. Eleven physical and

chemical properties were evaluated and related to four soil functions during six years, generating two soil quality indices. In addition, soil and water losses were assessed on standard plots and, subsequently related to the soil quality indices generated.

REFERENCES

ACOSTA, J. A. et al. Soil Water Content Prediction Using Electrical Resistivity Tomography (ERT) in Mediterranean Tree Orchard Soils. **Sensors**, v. 22, n. 4, 1 fev. 2022.

ALVARENGA, Â. A. et al. Nutritional Quality of Olives and Olive oil Produced in the Serra Da Mantiqueira from Brazil. **Agricultural Sciences**, v. 08, n. 07, p. 518–526, 2017.

APARECIDO, L. E. DE O. et al. Agroclimatic Mapping for Olive Cultivation in Brazil: Pinpointing Optimal Growing Regions. **Journal of the Science of Food and Agriculture**, 3 jan. 2023.

ARMENISE, E. et al. Developing a soil quality index to compare soil fitness for agricultural use under different managements in the mediterranean environment. **Soil and Tillage Research**, v. 130, p. 91–98, 2013.

BENIAICH, A. et al. Determination of vegetation cover index under different soil management systems of cover plants by using an unmanned aerial vehicle with an onboard digital photographic camera. **Semina:Ciencias Agrarias**, v. 40, n. 1, p. 49–66, 2019.

BENIAICH, A. et al. Assessment of soil erosion in olive orchards (Olea Europaea L.) Under cover crops management systems in the tropical region of Brazil. **Revista Brasileira de Ciencia do Solo**, v. 44, p. 1–22, 2020.

BENIAICH, A. et al. Spontaneous vegetation as an alternative to cover crops in olive orchards reduces water erosion and improves soil physical properties under tropical conditions. **Agricultural Water Management**, v. 279, p. 108186, abr. 2023.

BENITES, V. DE M. et al. Soil and vegetation on the high altitude rocky complexes of the Mantiqueira and Espinhaço mountain. **Floresta e Ambiente**, v. 10, n. 1, p. 76–85, 2003.

CÂNDIDO, B. M. et al. Indicator indexing methods in assessment of soil quality in relation to water erosion. **Revista Brasileira de Ciência do Solo**, v. 39, n. 2, p. 589–597, 2015.

CANISARES, L. P. et al. Soil microstructure alterations induced by land use change for sugarcane expansion in Brazil. **Soil Use and Management**, v. 36, n. 2, p. 189–199, 1 abr. 2020.

CELANO, G. et al. Evaluation of soil water content in tilled and cover-cropped olive orchards by the geoelectrical technique. **Geoderma**, v. 163, n. 3–4, p. 163–170, 15 jul. 2011.

GUIMARÃES, D. V. et al. Dynamics and losses of soil organic matter and nutrients by water erosion in cover crop management systems in olive groves, in tropical regions. **Soil and Tillage Research**, v. 209, n. December 2019, 2021.

KARLEN, D.L. et al. Soil quality: a concept, definition, and framework for evaluation. **Soil Science Society of America journal**, v. 61, 1997.

LIMA, G. C. et al. Spatialization of soil quality index in the sub-basin of Posses, Extrema, Minas Gerais. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 20, n. 1, p. 78–84, 2016.

MARION, L. F. et al. Development of a soil quality index to evaluate agricultural cropping systems in southern Brazil. **Soil and Tillage Research**, v. 218, 1 abr. 2022.

MELO, L. B. B. DE et al. Effect of compaction on the relationship between electrical resistivity and soil water content in Oxisol. **Soil and Tillage Research**, v. 208, 1 abr. 2021.

MELO, L. B. B. et al. Spatial and temporal electrical resistivity dynamics in a dense Ultisol under deep tillage and different citrus root-stocks. **Soil and Tillage Research**, v. 228, 1 abr. 2023.

OLIVEIRA, E. M. DE et al. Cover crop management systems improves soil quality and mitigate water erosion in tropical olive orchards. **Scientia Horticulturae**, v. 330, p. 113092, 15 abr. 2024.

SANTANA, M. L. T. et al. Impacts of Land Use Changes on Soil Functions and Water Security: Insights from a Three-Year-Long Study in the Cantareira System, Southeast of Brazil. **Sustainability**, v. 15, n. 18, p. 13395, 7 set. 2023.

SANTOS, R. D. DOS et al. **Manual de descrição e coleta de solo no campo**. 7. ed. Viçosa: Sociedade Brasileira de Ciência do Solo, 2015. v. 1

SANTOS, W. P. DOS et al. Soil quality assessment using erosion-sensitive indices and fuzzy membership under different cropping systems on a Ferralsol in Brazil. **Geoderma Regional**, v. 25, 2021.

SCHICK, J. et al. Water erosion in clayey inceptisol in different crop and tillage systems: I. Soil and water losses. **Revista Brasileira de Ciência do Solo**, v. 24, n. 1, p. 427–436, 2000.

SILVA, B. P. C. et al. Digital soil mapping including additional point sampling in Posses ecosystem services pilot watershed, southeastern Brazil. **Scientific Reports**, v. 9, n. 1, 1 dez. 2019.

SILVA, A. M. DA et al. Rainfall erosivity and erodibility of Cambisol (Inceptisol) and Latosol (Oxisol) in the region of Lavras, southern Minas Gerais state, Brazil. **Revista Brasileira de Ciência do Solo**, v. 33, n. 6, p. 1811–1820, 2009.

SILVA, L. F. DE O. DA et al. Quality variation of the olive oil in olive cultivars. **Bragantia**, n. 2, p. 202–209, 2012.

SIMON, C. DA P. et al. Soil quality literature in Brazil: A systematic review. **Revista Brasileira de Ciência do Solo**, v. 46, 2022.

STOOPS, G. **Guidelines for analysis and description of soil and regolith thin sections**. 2. ed. Hoboken: Madson SSSA, 2003. v. 1

VASU, D.; TIWARY, P.; CHANDRAN, P. A novel and comprehensive soil quality index integrating soil morphological, physical, chemical, and biological properties. **Soil and Tillage Research**, v. 244, 1 dez. 2024.

WREGE, M. S. et al. Potencial distribution of olive in Brazil and worldwide. **Revista Brasileira de Fruticultura**, v. 37, n. 3, p. 656–666, 1 jul. 2015.

SECOND PART - PAPERS

This paper was prepared in Elsevier format.

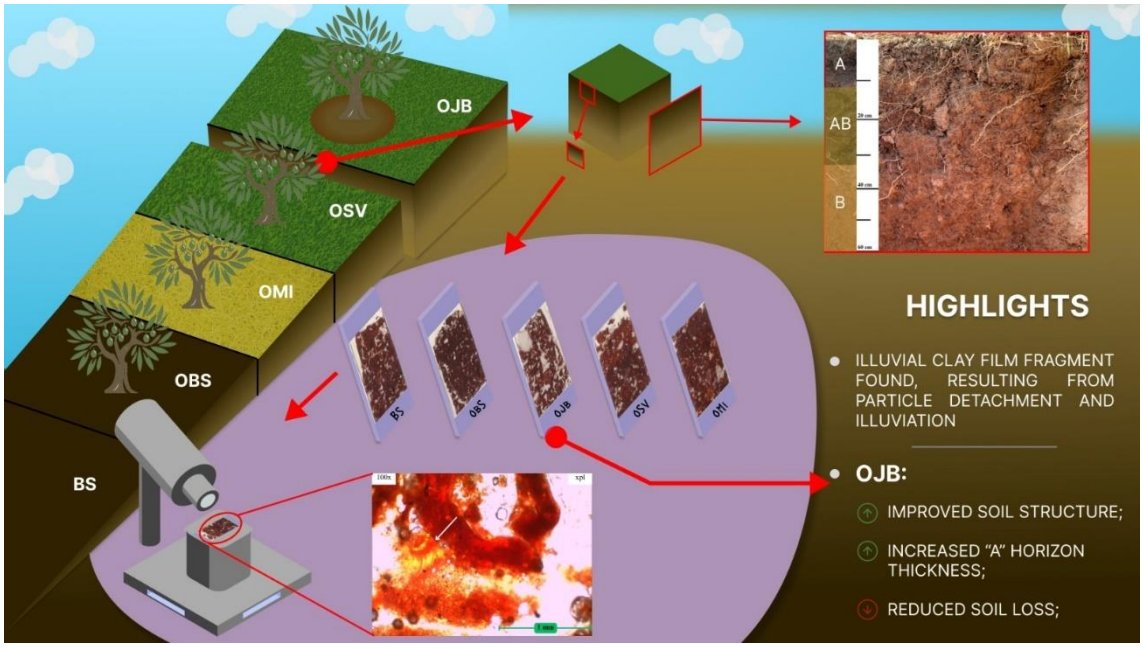
PAPER 1 – EFFECT OF SOIL COVER CROP MANAGEMENT SYSTEM ON OLIVE ORCHARDS: MORPHOLOGICAL AND MICROMORPHOLOGICAL ALTERATIONS IN A DYSTRUDEPT

Abstract

Olive production in Brazil is occurs in regions with shallow soils and steep slopes, requiring sustainable soil cover crop management to improve the surface layer and enhance soil structure. This study aimed to evaluate the morphology of a Dystrudept under different cover crop management systems through field and micromorphological analyses. An eight-year study was conducted to assess the effect of five cover crop management systems on soil structure and microstructure. Morphological descriptions were performed on five soil profiles, and undisturbed samples were collected from the vertical face of each pit for micromorphological analysis and thin-section interpretation. The treatment with olive trees and jack beans, followed by managed spontaneous vegetation, minimised soil loss over six years, enhancing soil structure, A horizon thickness, and total porosity. The presence of illuvial clay film fragments highlights the role of erosive forces in detaching and redistributing fine soil particle within the surface layer. Overall, cover crop management systems significantly influenced soil structural and microstructural properties, demonstrating their importance in maintaining soil integrity and mitigating degradation in olive-orchard regions.

Keywords: *Olea europaea* L., shallow soil, soil structure, tropical zone

Graphical abstract



1. Introduction

The olive tree (*Olea europaea* L.) is a temperate fruit tree native to the Mediterranean region and has been cultivated in Brazil for over a century (Aparecido et al., 2023; Wrege et al., 2015). Brazil has suitable areas for the development of this crop, limited to the south and southeast regions, with the state of Minas Gerais standing out as the most suitable region, due to its climate and topography (Aparecido et al., 2023). In this region, olive trees have been typically adapted to sloping areas with shallow soils (Beniaich et al., 2022).

Several specific conditions may lead to high levels of soil erosion in olive orchards (Guimarães et al., 2021; Márquez-García et al., 2024; Oliveira et al., 2024; Zuazo et al., 2020). These include cultivation on bare soil, frequent episodes of erosive rainfall, low leaf cover along ridges, and the physiological requirement for large spacing (Guimarães et al., 2018; Oliveira et al., 2024). Erosion is particularly severe during periods of heavy rainfall, with soil loss rates exceeding 80 Mg ha^{-1} in a single month (Beniaich et al., 2023), making it one of the primary environmental challenges in olive cultivation (Márquez-García et al., 2024).

Inceptisols are one of the primary soil orders cultivated in tropical regions, such as Brazil, despite their limitations in depth, steep topography, high silt content, dense structure, and low water permeability (Silva et al., 2009; Skorupa et al., 2017). In this context, the management of cover crops has been recommended to enhance soil structure as well as its chemical and physical properties (Oliveira et al., 2024; Santos et al., 2021).

Soil cover crop management systems are conservation practices that effectively reduce soil and water losses and improve soil quality by influencing the physical and chemical properties of the soil (Cândido et al., 2015; Oliveira et al., 2024; Santos et al., 2021). They also modify the structure and diversity of the soil bacterial community, increase functional microbial activities (Arias-Giraldo et al., 2021), and prevent nutrient losses through erosion (Guimarães et al., 2021).

Soil physical properties play a crucial role in crop production, with those associated with soil structure representing key indicators of soil quality (Oliveira et al., 2024; Silva et al., 2015). Soil structure and aggregation are dynamic attributes that undergo modifications influencing water infiltration and, consequently, crop growth. Additionally, soil organic matter is a fundamental determinant in these processe (Kapur et al., 2007).

The visual assessment of soil structure can be conducted through the morphological description of soil profiles in the field, analysing each horizon or layer individually based on traditional pedological characterization (Santos et al., 2015). Additionally, evaluations using

undisturbed micromorphology enable the identification of distinct soil components and their spatial and temporal relationships, providing insights into the processes governing soil formation and the development of specific characteristics (Stoops, 2003).

Micromorphology provides a more detailed approaches than other methods for visualising soil microstructure, facilitating the elucidation of processes, mechanisms, pedogenesis parthways, and the behaviour and functioning of the soil system (Canisares et al., 2020; Santos et al., 2015). Despite the availability of various tools to investigate soil physical behaviour in response to land use and management changes, the impact of these practices on soil structure remains inadequately understood, particularly concerning microscale changes (Canisares et al., 2020).

This research aimed to evaluate the morphology of a Dystrudept subjected to different cover crop management systems through field analysis and micromorphological examination. The study hypothesizes that cover crop management systems exert a significant influence on alterations in soil structure and microstructure in a Dystrudept.

2. Material and methods

2.1 Fild experiment description

This research was conducted in erosion plots located within the experimental area of the Federal University of Lavras, Lavras, Minas Gerais, Brazil (21º13’20” S and 44º58’17” W), at an altitude 918 m a.s.l. (Fig. 1). The climate is classified as subtropical highland (Cwb) according to Köppen Climate Classification System (Alvares et al., 2014), with a mean annual rainfall of 1,383.4 mm and a mean annual temperature of 20.6 ºC (INMET, 2022). Winters are dry and cool, whereas summers are characterised by higher rainfall and daily average temperatures exceeding 22 ºC (Dantas et al., 2007). The soil is classified as Cambissolo Háplico Tb Distrófico according to the Brazilian Soil Classification System (Santos et al., 2018), corresponding to Dystrudept in Soil Taxonomy (Soil Survey Staff, 2022), and a Dystric Cambisol in the FAO Soil Classification System (IUSS Working Group WRB, 2022).

The field experiment started in 2015, when the erosion plots were installed and the olive trees were planted downslope. Throughout the evaluation period (2015-present) the experimental area was divided into five treatments. In each plot, four olive trees were planted, 4 m apart from each other, and 5 m apart from the trees in contiguous plot. The cultivar planted was Arbequina, the most cultivated in Brazil (Borges et al., 2017). Each tree planting hole (40 cm deep and 40 cm wide) received 100 g of limestone, 20 liters of manure, 500 g of superphosphate, and 200 g of potassium chloride. For the annual fertilization in the

2015/2016 season, we applied 50 g of ammonium sulfate to each tree in November, December, and January. For the annual fertilization in the 2016/2017 season, we applied 100 g of ammonium sulfate, 50 g of potassium chloride, and 20 g of boric acid to each tree in October. Still in the 2016/2017 season, we applied 100 g of ammonium sulfate, 50 g of potassium chloride to each tree in December. In January, we applied 100 g of ammonium sulfate to each tree. During the dry season, we manually irrigated the olive plantation to meet the plants' water demands.

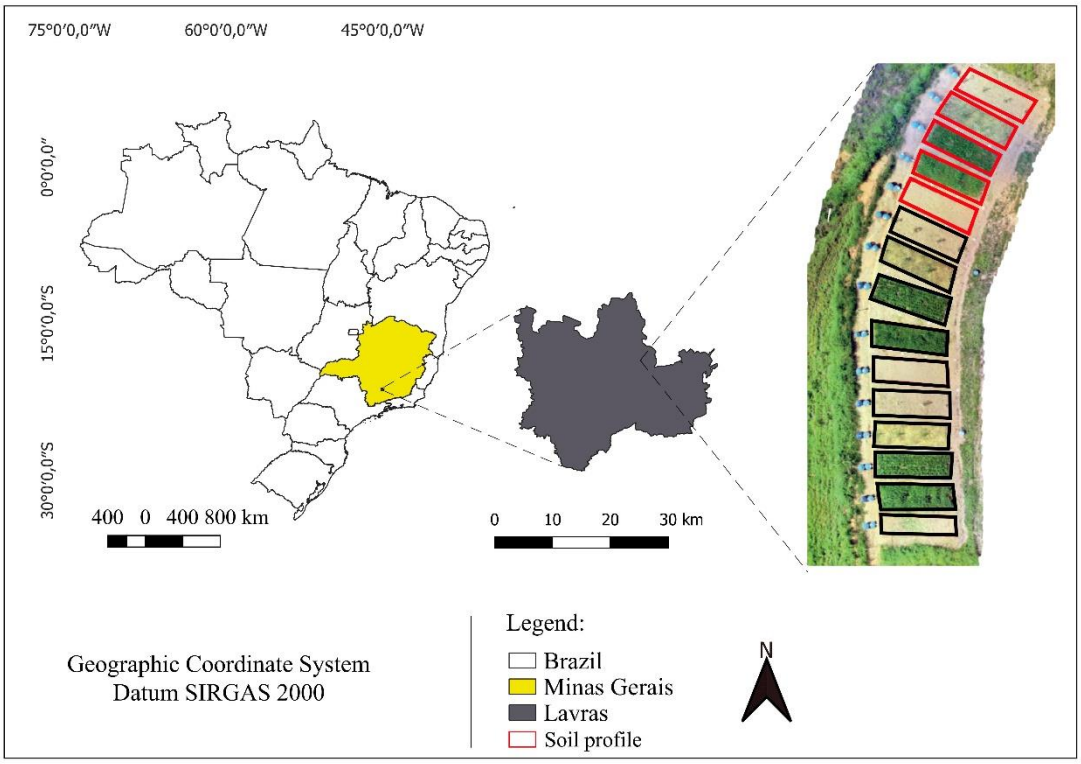


Fig. 1. Location of the experimental area (Lavras, Minas Gerais, Brazil).

The experimental design consisted of five treatments (soil cover crop management systems) spanning the period from 2015 to 2023. The five treatments were (Table 1): 1) BS – bare soil without olive trees: soil was maintained free of weeds and vegetation by chemical weed control and manual weeding; 2) OBS – olive tree planted in bare soil; 3) OJB – olive tree associated with jack beans (*Canavalia ensiformis* L.) in 2015/2016 and 2016/2017, and olive trees crowned associated with mowed spontaneous vegetation in 2017/2021; 4) OSV – olive tree associated with mowed spontaneous vegetations; 5) OMI – olive tree associated with millet (*Pennisetum glaucum* L.) in 2015/2016, then with sunn hemp (*Crotalaria juncea* L.) in 2016/2017 and olive associated with spontaneous vegetation treated with herbicide in 2017/2021. Between 2021 to 2023, the experiment remained fallow with the olive trees, according to the treatments.

Table 1. Description of five study treatments.

Treatment	2015/2016	2016/2017	2017/2021	2021/2023
BS	----------Bare soil without olive trees----------			RF
OBS	----------Olive trees on bare soil----------			RF with olive trees
OJB	--Jack beans-	--Jack beans--	---------SV – crowned and mowed---------	RF with olive trees
OSV	----------SV – mowed----------			RF with olive trees
OMI	-Millet-	-Sunn hemp-	----------SV - herbicide----------	RF with olive trees

RF – Remained Fallow; SV – Spontaneous Vegetations.

The spontaneous vegetation in 2016 and 2017 consisted of grasses, being *Brachiaria decumbens* Stapf the dominant species, followed by *Digitaria sanguinalis* L., *Melinis minutiflora* P. Beauv., *Eleusine indica* L. and some broadleaf species such *Euphorbia heterophylla* L., *Amaranthus viridis* L., *Emilia fosbergii* Nicolson, *Ipomoea acuminata* Roem., *Conyza bonariensis* L., *Oxalis corniculata* L., and *Bidens pilosa* L.. In 2021, a new survey was carried out, which the following composition: the main dominant species were *Brachiaria decumbens* Stapf and *Desmodium incanum* DC., and in a smaller proportion, *Amaranthus viridis* L., *Bidens pilosa* L., *Emilia fosbergii* Nicolson and individuals of *Vernonia polyanthes* (Spreng.) Less..

Cover crops (*C. ensiformis* L - jack beans, *P. glaucum* L. - millet and *C. juncea* L. - sunn hemp) were manually seeded at the beginning of the rainy season, on November 2015 and 2016. In the jack bean treatment, the furrows were spaced at every 50 cm in a density of 8 seeds m^{-1}. In the millet and sunn hemp treatments, the spacing used was 25 cm with densities of 90 and 40 seeds m^{-1}, respectively. Regarding the fertilization of the cover crops, 500 kg ha^{-1} of NPK (8:28:16), in the first crop season and 250 kg ha^{-1} of NPK (8:28:16), in the second crop season, were applied. For chemical weed control in BS, OBS and OMI plots, glyphosate was used.

2.2 Sampling and sample preparation for morphological and micromorphological description

In 2023, a soil profile was sampled in the center of one plot per treatment to a depth of 0-60 cm for morphological description (Santos et al., 2015). Subsequently, undisturbed soil samples were collected on the vertical face of the pit, from a depth of 0-10 cm, with known orientation using Kubiena boxes.

These samples were initially air dried and subsequently subjected to a controlled drying process, including oven drying at 40 ºC for seven days, followed by 60 ºC for three days, and finally 100 ºC for 24 hours. This multi-step drying regime aimed to minimize the

development of cracks associated with rapid desiccation. After this drying phase, the samples were impregnated with epoxy resin and de-aerated under vacuum to ensure the removal of air bubbles and facilitate thorough resin infiltration. The samples were then hardened at 100 ºC for 4 hours, and cured at 140 ºC for 4 hours. The resulting resin block were vertically cut with respect to the soil surface, polished, and mounted onto glass slides. The prepared slides were first trimmed and polished to a thickness of 100 μm and scanned. Finally trimmed and polished to an ideal thickness of 30 μm to carry out the micromorphological description of the thin sections (Stoops, 2003).

2.3 Soil characterization

Soil physical and chemical attributes were evaluated at the beginning of June during the dry period, in 2016 and 2021. Three points were sampled in each plot, distributed in the top, middle and bottom positions, collecting samples from two depths, 0-20 cm, and 20–40 cm. Particle size distribution in disturbed soil samples was determine by the hydrometer method (Dane and Topp, 2002).

Undisturbed soil samples were collected using metal cores (diameter of 6 cm and height of 8 cm). Soil bulk density (Bd), total porosity (TP), macro (MaP) and microporosity (MiP) (pores < 0.05 mm of diameter) were determined (Dane and Topp, 2002). Soil aggregate stability in water occurred by the was wet-sieving method (Yoder procedure) and geometric mean diameter (GMD) were calculated (Kemper and Rosenau, 1986; Silva et al., 2017).

Soil and water losses were evaluated on the erosion plots, with size 12 m in length and 4 m in width (Wischmeier and Smith, 1978). The mean slope of the plots was 0.23 m m^{-1}. Drainage and sediment collection were carried out for each erosion event, using two 250 L tanks installed at the end of each plot (Cogo et al., 2003). The two tanks were connected by a Geib-type divider, with nine inlet windows, so that when the first tank was completely full, 1/9 of the runoff volume would be conducted to the second tank.

Soil organic matter (SOM) was determined in the < 2 mm soil using oxidation with $Na_2Cr_2O_7$4N + $H_2SO_4$10N method (Walkley and Black, 1934). The pH was determined using H_2O in the ratio 1:2.5. Exchangeable K and available P were determined using the Melich I extractor, while exchangeable Ca, Mg, and Al were determined using the KCl 1 mol L^{-1} extractor. The potential acidity (H+Al) was determined using SMP extractor. The methods used to assess these soil chemical attributes are described (Silva et al., 2017).

2.4 Statistical analysis

The normality, heteroscedasticity and variance test premises of the soil physical and chemical attributes, soil and water losses data were analyzed through linear models, using graphical visualization (Kozak and Piepho, 2018) and numerical tests (Peña and Slate, 2006). When necessary, logarithmic transformations, square root or removal of outlier methods were applied.

Once all the data met the premises, an analysis of variance (ANOVA) was performed considering the design in five treatments (cover crop management systems) and three randomized blocks, through the F test ($P < 0.05$). When ANOVA null hypothesis was rejected, comparisons were performed using the Tukey test ($P < 0.05$) to determine significant differences among means.

3. Results

3.1. Soil physical properties and water erosion

The results of bulk density, total porosity, aggregate size and stability, soil and water losses are summarized in Table 2, which shows the evolution of these soil attributes under five different treatments from 2016 to 2021.

In the 0-20 cm layer, soil bulk density was not affected by cover crop management. On the other hand, in the 20-40 cm soil layer, the OMI treatment was the only cover crop management system that maintained the same pattern in the two years evaluated, reducing soil bulk density in 2016, compared to the OBS treatment and in 2021 compared to both the OBS and BS treatments.

In general, the soil physical properties of macro- and microporosity were not affected by the treatments at the two soil layers and years evaluated. However, for total porosity, there was an increase in pore distribution in the OJB treatment in the soil depth of 20-40 cm in 2016, but not in 2021, suggesting an improvement in soil structuring in the first year of the study.

Of the two variables assessing aggregate stability, the geometric mean diameter was able to detect an effect of soil cover crop management, with the OBS treatment showing the lowest value in the 0-20 cm layer in 2016 compared to the other management systems. In 2021, the soil cover crop management systems had no effect on these soil variables.

Table 2. Soil physical and chemical properties of the Dystrudept under cover crops management systems in olive orchard in 2016 and 2021.

Physical	Soil layer (cm)	2016						2021					
			BS	OBS	OJB	OSV	OMI		BS	OBS	OJB	OSV	OMI
Bulk density ($g\ cm^{-3}$)	0-20	ns	1.45	1.4	1.49	1.5	1.55	ns	1.20	1.29	1.25	1.21	1.33
	20-40	*	1.54 b	1.66 a	1.59 ab	1.57 b	1.54 b	*	1.35 a	1.47 a	1.37 a	1.35 a	1.22 b
Macroporosity ($cm^3\ cm^{-3}$)	0-20	ns	0.30	0.30	0.28	0.29	0.28	ns	0.18	0.18	0.18	0.16	0.17
	20-40	ns	0.28	0.31	0.31	0.30	0.29	ns	0.14	0.14	0.15	0.14	0.20
Microporosity ($cm^3\ cm^{-3}$)	0-20	ns	0.28	0.28	0.29	0.28	0.29	ns	0.45	0.49	0.49	0.48	0.49
	20-40	ns	0.28	0.28	0.29	0.29	0.29	ns	0.24	0.25	0.25	0.25	0.22
Total porosity ($cm^3\ cm^{-3}$)	0-20	ns	0.58	0.57	0.57	0.57	0.57	ns	0.40	0.44	0.44	0.41	0.43
	20-40	*	0.56 b	0.59 ab	0.60 a	0.59 ab	0.58 ab	ns	0.37	0.30	0.38	0.36	0.41
Geometric mean diameter (mm)	0-20	ns	4.16	3.62	4.20	3.78	3.91	ns	4.25	4.24	4.84	4.56	4.47
	20-40	ns	4.09	3.60	3.52	3.29	3.38	ns	2.01	2.89	2.89	3.37	3.17
Chemical													
Soil organic matter ($g\ kg^{-1}$)	0-20	ns	5.1	2.5	3.7	3.4	5.4	ns	18.5	16.8	27.7	26.4	22.9
	20-40	ns	8.1	7.6	7.0	8.9	8.4	ns	5.8	7.8	6.2	12.0	07.6
pH	0-20	ns	5.04	5.19	5.16	5.19	5.43	ns	4.98	5.03	5.57	5.63	5.18
	20-40	ns	5.10	4.89	5.12	5.52	5.33	ns	5.32	5.48	5.18	5.72	5.25
Available P ($mg\ dm^{-3}$)	0-20	ns	2.53	2.57	1.37	1.50	1.86	*	3.26 ab	2.08 b	3.16 ab	2.97 ab	3.79 a
	20-40	ns	0.82	0.42	0.44	0.75	0.54	ns	0.59	0.33	1.08	0.67	0.76
Exchangeable Al^{3+} ($mg\ dm^{-3}$)	0-20	ns	0.17	0.16	0.22	0.13	0.15	ns	0.41	0.34	0.29	0.35	0.34
	20-40	ns	0.21	0.24	0.28	0.13	0.21	ns	0.08	0.07	0.13	0.10	0.10
Sum of bases ($cmol_c\ dm^{-3}$)	0-20	ns	2.30	2.31	2.26	2.38	2.66	*	2.10 b	2.89 ab	4.19 a	3.95 a	3.43 ab
	20-40	ns	1.79	1.61	1.32	1.80	1.61	ns	2.26	2.35	1.77	2.40	1.89
CEC at pH 7 ($cmol_c\ dm^{-3}$)	0-20	ns	4.50	4.34	4.36	4.70	4.85	ns	5.54	5.07	5.90	5.83	5.91
	20-40	ns	4.06	3.79	3.88	3.61	3.26	*	3.90 b	5.21 a	3.60 b	4.25 b	3.50 b
Water erosion													
Soil loss ($Mg\ ha^{-1}\ period^{-1}$)	-	*	290.2 a	301.3 a	86.5 ab	61.3 ab	14.6 b	*	6.9 a	55.5 a	0.1 c	0.4 bc	0.4 bc
Water loss ($mm\ period^{-1}$)	-	*	565.0 a	568.0 a	270.0 b	116.0 c	159.0 bc	*	34.0 a	42.2 a	39.7 a	39.2 a	3.23 b

Values are the mean of treatments. For each treatment, means followed by different letters in the line differ statistically according to the Tukey test ($P<0.05$). ns: not significance. BS: bare soil in 2015-2021 and fallow land in 2021-2023; OBS: olive tree on bare soil in 2015-2021 and fallow land in 2021-2023; OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021, and fallow land in 2021-2023; OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021 and fallow land in 2021-2023; OMI: olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021, and fallow land in 2021-2023.

3.3. Soil morphological description

The soil loss results showed that the BS and OBS treatments had the highest values in both years, highlighting the importance of keeping the soil covered. In general, the OJB treatment was the best at preventing soil loss from the first year of implementation. Similarly, the BS and OBS treatments also showed higher water losses in 2016, but in 2021 only the OMI treatment was able to prevent runoff and showed lower water losses.

The results of soil chemical properties (Table 2) in 2016 showed that most of the variables assessed were not affected by the soil cover crop management system. On the other hand, after six years of cultivation, there was an effect of soil cover crop management on the olive crop for the chemical attributes evaluated, especially in the surface (0-20 cm).

The variables soil organic matter, pH and exchangeable Al showed no differences between the soil cover crop management systems at any of the depths studied in 2021 (Table 2). In the 0-20 cm layer, the treatments that maintained the soil cover performed better, indicating the importance of its implementation. The OJB and OSV treatments were the most efficient in sum of bases, and the OMI treatment in relation of available phosphorus. In the 20-40 cm layer, the properties of available phosphorus and sum of bases were not influenced by the soil cover crop management systems in 2021. The OBS treatment was the best performer with the highest values for cation exchange capacity at pH 7.

3.2. Soil chemical properties

The morphological description of the soil horizons under different cover crop management systems (BS, OBS, OJB, OSV, and OMI) revealed distinct variations in structure, consistency, and color, highlighting the impact of management practices on soil properties and morphology.

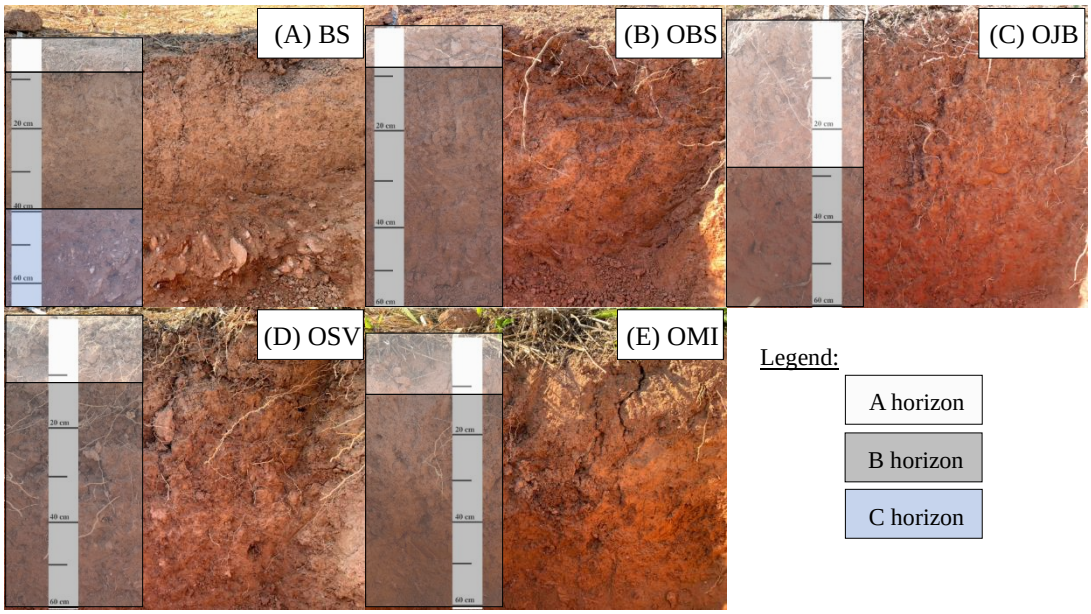


Fig. 2. Soil profiles: (A) BS - bare soil in 2015-2021 and fallow land in 2021-2023; (B) OBS - olive tree on bare soil in 2015-2021 and fallow land in 2021-2023; (C) OJB – olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021, and fallow land in 2021-2023; (D) OSV - olive tree intercropped with mowed spontaneous vegetation in 2015-2021 and fallow land in 2021-2023; (E) OMI - olive tree intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021, and fallow land in 2021-2023.

In the BS treatment, four horizons were identified: A (0-9 cm), B1 (9-31 cm), BC (31-42 cm), and C (42-60+ cm). This treatment showed a well-defined C horizon, indicative of the presence of saprolitic material at a shallow depth (Table 2, Fig. 2E). The structure evolved from weakly developed angular and subangular blocks in the A horizon to a moderately developed structure in the deeper horizons, with medium-sized blocks throughout. The color ranged from 10 YR 3/6 in the A horizon to a lighter 10YR 6/8 in the C horizon, reflecting a transition to the parent material. In contrast, the OBS treatment had a more abrupt transition between horizons, and no distinct C horizon was observed. The profile consisted of an A horizon (0-7 cm), AB horizon (7-24 cm), and B horizons (24-60+ cm). The structure was consistently stronger than in BS, with larger, angular blocks in the A and AB horizons. The B horizon had very hard consistency, with a color progression from 10R 4/6 (moist) to 10R 5/8 (dry) (Table 2, Fig. 2B), indicating deeper soil weathering but no significant parent material exposure.

Table 2. Morphological description of the different cover crop managements.

Treatment	Morphological Description
BS	**A (0-9 cm):** *Structure:* angular and subangular blocks, medium, weak to moderate; *Consistency:* dry-slightly hard, moist-very friable. Plastic, slightly sticky; *Munsell color:* 10R 3/6 (moist) and 10R 6/6 (dry); *Transition:* smooth and clear. **B1 (9-31 cm):** *Structure:* angular and subangular blocks, medium to large, moderate; *Consistency:* dry-slightly hard, moist-firm. Very plastic, sticky; *Munsell color:* 10R 4/6 (moist) and 10R 7/4 (dry); *Transitional horizon:* smooth and clear. **BC (31-42 cm):** *Structure:* angular and subangular blocks, medium, weak to moderate; *Consistency:* dry-hard, moist-friable. Slightly plastic, slightly sticky; *Munsell color:* 10R 4/8 (moist) and 10R 6/6 (dry); *Transitional horizon:* smooth and abrupt. **C (42-60+ cm):** *Structure:* angular blocks, small to medium, moderate; *Consistency:* dry-slightly hard, moist-friable. Slightly plastic, slightly sticky; *Munsell color:* 10 R 4/6 (moist) and 10R 7/8 (dry). *Observation*: presence of saprolitic material with color 10YR 6/8 (moist) and 10YR 6/8 (dry); presence of gravel.
OBS	**A (0-7 cm):** *Structure:* angular and subangular blocks, medium to large, strong; *Consistency:* dry-hard, moist-firm. Very plastic, slightly sticky; *Munsell color:* 10R 4/6 (moist) and 10R 7/6 (dry); *Transitional horizon:* smooth and abrupt. **AB (7-24 cm):** *Structure:* angular blocks, medium to large, strong; *Consistency:* dry-very hard, moist-firm. Very plastic, slightly sticky; *Munsell color:* 10R 4/8 (moist) and 10R 7/4 (dry); *Transitional horizon:* smooth and clear. **B1 (24-40 cm):** *Structure:* angular and subangular blocks, medium to large, strong; *Consistency:* dry-very hard, moist-firm. Very plastic, slightly sticky; *Munsell color:* 10R 4/6 (moist) and 10R 5/8 (dry); *Transitional horizon:* smooth and clear. **B2 (40-60+ cm):** *Structure:* angular and subangular blocks, medium to large, strong; *Consistency:* dry-very hard, moist-firm. Very plastic, slightly sticky; *Munsell color:* -
OJB	**A1 (0-6 cm):** *Structure:* angular blocks, medium, moderate; *Consistency:* dry-soft, moist-very friable. Slightly plastic, slightly sticky; *Munsell color:* 2.5YR 2.5/4 (moist) and 2.5YR 4/3 (dry); *Transitional horizon:* smooth and clear. **A2 (6-20 cm):** *Structure:* subangular blocks, large, moderate; *Consistency:* dry-slightly hard, moist-very friable. Very plastic, slightly sticky; *Munsell color:* 2.5YR 3/6 (moist) and 2.5YR 5/6 (dry); *Transitional horizon:* smooth and clear. **AB (20-39 cm):** *Structure:* angular and subangular blocks, medium to large, strong; *Consistency:* dry-slightly hard, moist-firm. Very plastic, sticky; *Munsell color:* 2.5YR 5/8 (moist) and 2.5YR 7/6 (dry); *Transitional horizon:* smooth and clear. **B (39-60+ cm):** *Structure:* angular and subangular blocks, medium to large, strong; *Consistency:* dry-hard, moist-firm. Very plastic, very sticky; *Munsell color:* 2.5YR 4/8 (moist) and 2.5YR 5/8 (dry).
OSV	**A (0-12 cm):** *Structure:* subangular blocks, medium, strong; *Consistency:* dry-slightly hard, moist-firm. Very plastic, slightly sticky; *Munsell color:* 10R 3/3 (moist) and 10R 6/3 (dry); *Transitional horizon:* smooth and clear. **AB (12-33 cm):** *Structure:* angular and subangular blocks, medium to large, moderate; *Consistency:* dry-slightly hard, moist-firm. Very plastic, slightly sticky; *Munsell color:* 2.5YR 4/6 (moist) and 10R 5/4 (dry); *Transitional horizon:* smooth and clear. **B (33-60+ cm):** *Structure:* angular and subangular blocks, medium to large, moderate; *Consistency:* dry-hard, moist-friable. Very plastic, sticky; *Munsell color:* 10R 4/6 (moist) and 10R 5/8 (dry);
OMI	**A (0-12 cm):** *Structure:* subangular blocks, medium to large, moderate; *Consistency:* dry-slightly hard, moist-firm. Plastic, slightly sticky; *Munsell color:* 10R 3/4 (moist) and 10R 6/4 (dry); *Transitional horizon:* smooth and clear. **BA (12-26 cm):** *Structure:* angular and subangular blocks, medium to large, strong; *Consistency:* dry- slightly hard, moist-friable. Very plastic, slightly sticky; *Munsell color:* 10R 4/8 (moist) and 10R 5/8 (dry); *Transitional horizon:* smooth and gradual. **B (26-60+ cm):** *Structure:* angular and subangular blocks, medium to large, strong; *Consistency:* dry-hard, moist-friable. Plastic, slightly sticky; *Munsell color:*10R4/6 (moist) and 10R4/6 (dry).

The OJB treatment showed a more pronounced A horizon, which was divided into an A1 horizon (0-6 cm), A2 horizon (6-20 cm), AB horizon (20-39 cm). Additionally, it also presented a B horizon (39-60+ cm) (Table 2, Fig. 1C). The structure was more moderate in the surface layers and became progressively stronger in the deeper layers. The colors, particularly in the A horizons, were darker and redder (2.5YR 2.5/4 moist and 2.5YR 4/3 dry), indicating a higher organic matter content and more intense weathering compared to BS and OBS.

In the OSV treatment, an A horizon was observed (0-12 cm), with a strong subangular blocky structure and firm consistency (Table 2, Fig. 1D). The profile included AB (12-33 cm) and B (33-60+ cm) horizons. The color of the A horizon was darker than in other treatments (10R 3/3 moist and 10R 6/3 dry), while the B horizon displayed strong red hues (10R 4/6 moist), suggesting more advanced soil development. Finally, the OMI treatment had a similar profile to OSV, with an A horizon (0-12 cm), BA horizon (12-0.26 cm), and a B horizon (26-60+ cm) (Table 2, Fig. 1D). The structure was consistently moderate to strong, with a notable shift to a more intense red color in the B horizon (10R 4/6 moist), indicative of advanced pedogenic processes and potential soil aggregation (Table 2, Fig. 1E).

3.4. Soil micromorphological description

The scanned thin sections of the vertical soil surface (Fig. 3) revealed distinct morphological differences among treatments in terms of porosity (macroporosity), structure, and colour. The BS, OBS, and OJB treatments exhibited continuous vertical pores, in contrast to the OSV and OMI treatments, which displayed high porosity but lacked visible connectivity. Additionally, the OJB treatment showed a noticeable presence of angular gneiss gravel. Finally, the OSV treatment exhibited a reddish coloration in the initial of the thin section compared to the rest of the profile.

The micromorphological analysis revealed distinct differences in micro structure and composition across the various treatments. In the BS treatment, the microstructure consisted of angular blocks, moderately to weakly separated, with planar and vughs voids and a double-spaced porphyric distribution of coarse materials such as quartz grains. The micromass was brown-reddish and speckeld. The pedofeatures was Fe nodules (Table 4, Fig. 4). The OBS treatment (olive planted in bare soil) exhibited similar structural characteristics to BS, with moderately to weakly separated angular

blocks, planar, vughs and chambers voids. However, the micromass was poro- and granostriated. The pedofeatures was Fe nodules in dissolution (Table 4, Fig. 5).

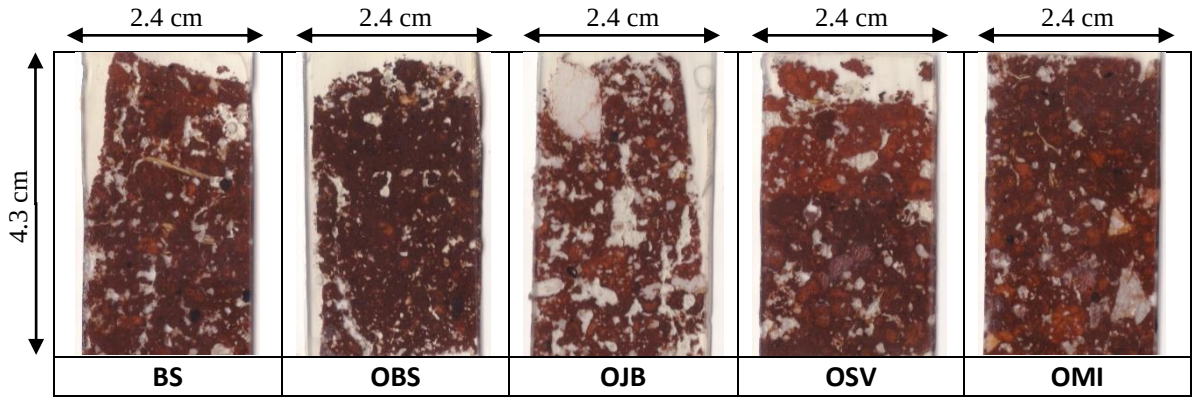


Fig. 3. Scanned images of thin sections of soil (depth of 0-4.3 cm and width of 2.4 cm, with a thickness of 0.01 cm). BS: bare soil in 2015-2021 and fallow land in 2021-2023; OBS: olive tree on bare soil in 2015-2021 and fallow land in 2021-2023; OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021, and fallow land in 2021-2023; OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021 and fallow land in 2021-2023; OMI: olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021, and fallow land in 2021-2023.

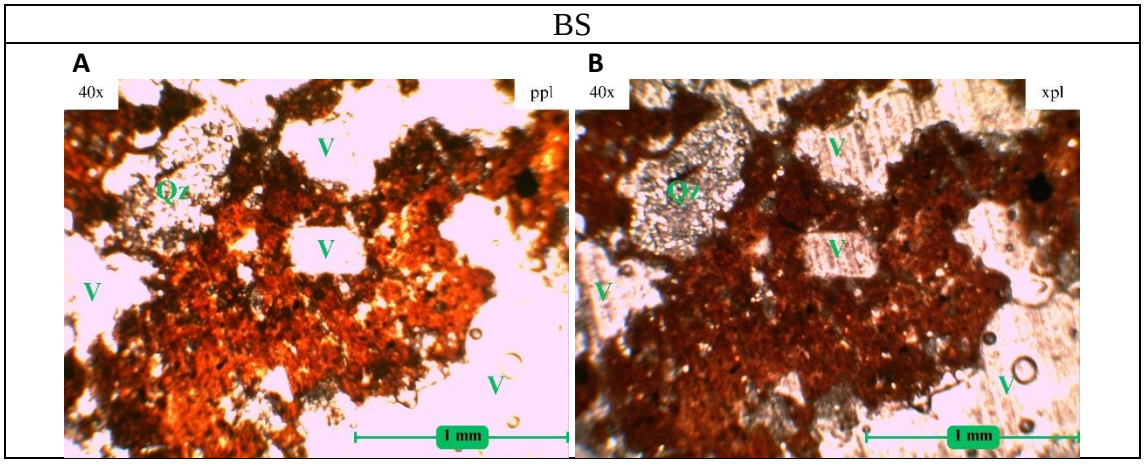


Fig. 4. Soil microstructure of BS: bare soil in 2015-2021 and fallow land in 2021-2023. A: ppl – plane-polarized light; B: xpl – cross-polarized light.

In contrast, the OJB treatment displayed more developed micromorphological features, with the presence of iron nodules and a strongly impregnated matrix. The microstructure remained angular with weak separation, but the poro- and granostriated micromass indicated improved organic content compared to BS and OBS. Presence of planar and vughs voids. This intercropping system promoted more advanced soil formation processes (Table 4, Fig. 6). The OSV treatment (olive intercropped with mowed spontaneous vegetation) showed a similar microstructure, with moderately

separated angular blocks, with planar, vughs, and chambers voids. However, the micromass was speckled and crystallitic, and the pedofeatures included remnant of clay coating.

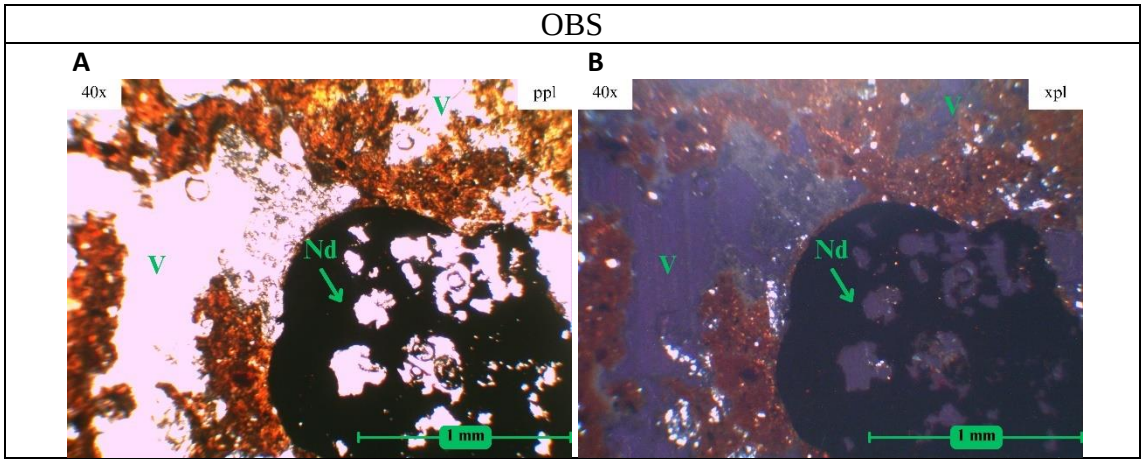


Fig. 5. Soil microstructure of OBS: olive tree on bare soil in 2015-2021 and fallow land in 2021-2023. A: ppl – plane-polarized light; B: xpl – cross-polarized light.

Lastly, the OMI treatment (olive intercropped with millet) demonstrated micromorphological features similar to OJB, with iron nodules. The micromass was poro- and granostriated, and root fragments were observed, reflecting a higher degree of organic matter incorporation and enhanced soil development under this treatment. Presence of planar, vughs, and chambers voids (Table 4, Fig. 8).

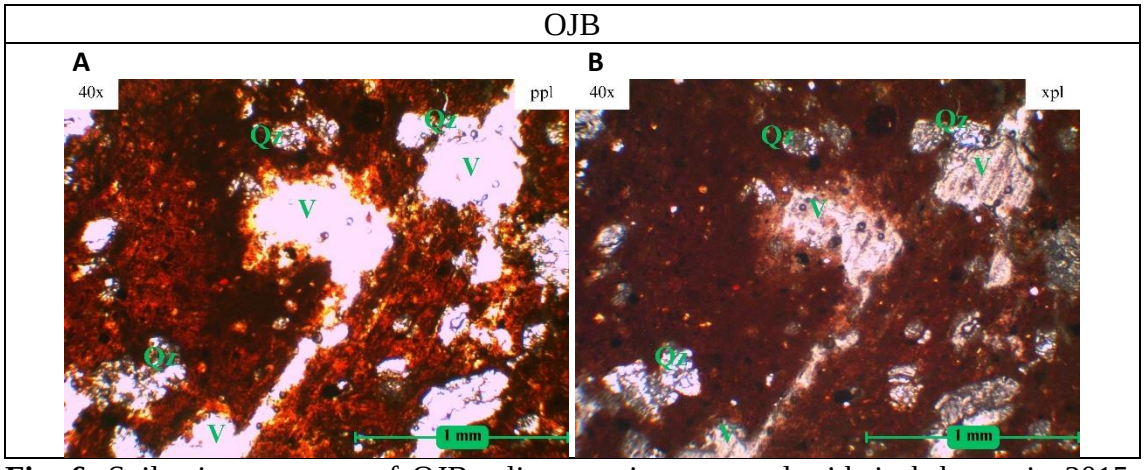


Fig. 6. Soil microstructure of OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021, and fallow land in 2021-2023. A: ppl – plane-polarized light; B: xpl – cross-polarized light.

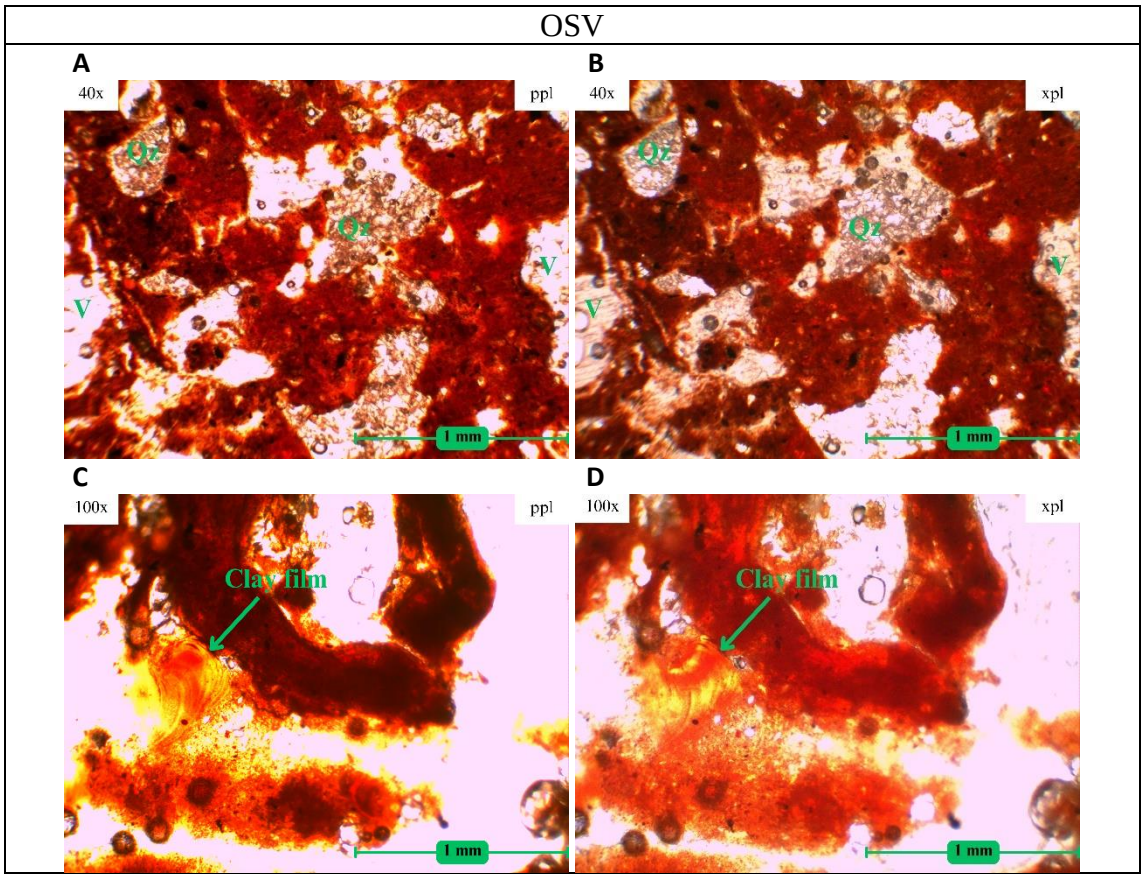


Fig. 7. Soil microstructure of OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021 and fallow land in 2021-2023. A and C: ppl – plane-polarized light; B and D: xpl – cross-polarized light.

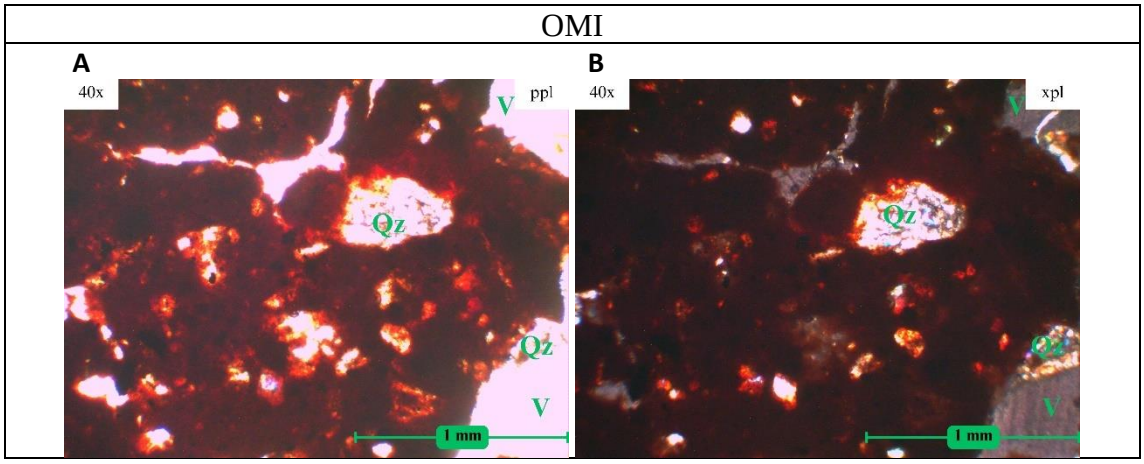


Fig. 8. Soil microstructure of OMI: olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021, and fallow land in 2021-2023. A: ppl – plane-polarized light; B: xpl – cross-polarized light.

Table 4. Micromorphological description of the different cover crop managements.

Management	Micromorphological Description
BS	*Microstructure:* angular blocks, moderately to weakly separated. *Voids:* planar and vughs. *c/f Limit and related distribution:* double spaced porphyric type. *Coarse material:* quartz grains e Fe nodules. *Organic Material:* *Micromass:* Speckeld. Brown-reddish coloration. *Pedofeatures:* Fe nodules.
OBS	Microstructure: angular blocks, moderately to weakly separated. Voids: planar, vughs and chambers. c/f Limit and related distribution: double spaced porphyric type. Coarse material: quartz grains and Fe nodules in involution. Organic Material: Micromass: crystallitic, poro- and granostriated. Brown-reddish coloration. Pedofeatures: relict Fe nodules in dissolution.
OJB	Microstructure: angular blocks, moderately to weakly separated. Voids: planar and vughs. c/f Limit and related distribution: double spaced porphyric type. Coarse material: quartz grains and iron nodules. Organic Material: Micromass: crystallitic, poro- and granostriated. Brown-reddish coloration. Pedofeatures: matrix pedofeature strongly impregnated
OSV	Microstructure: angular blocks, moderately to weakly separated. Voids: planar, vughs and chambers. c/f Limit and related distribution: 20μm and double spaced porphyric type, strial with granostriated. Coarse material: quartz grains. Organic Material: Micromass: crystallitic and speckled. Brown-reddish coloration. Pedofeatures: remnant of clay coating
OMI	Microstructure: angular blocks, moderately to weakly separated. Voids: planar, vughs and chambers. c/f Limit and related distribution: double spaced porphyric type. Coarse material: quartz grains and iron nodules. Organic Material: root fragment. Micromass: crystallitic, poro- and granostriated. Brown-reddish coloration. Pedofeatures: matrix pedofeature strongly impregnated

BS: bare soil in 2015-2021 and fallow land in 2021-2023; OBS: olive tree on bare soil in 2015-2021 and fallow land in 2021-2023; OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021, and fallow land in 2021-2023; OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021 and fallow land in 2021-2023; OMI: olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021, and fallow land in 2021-2023.

4. Discussion

4.1. Soil physical properties and water erosion

The different cover crop management systems in olive growing in the first hydrological year (2015/2016) seemed to have a stronger impact, especially on some properties (bulk density, total porosity, weighted mean diameter, soil loss and water loss), if compared to BS and OBS. Bagnall et al. (2022) state that bulk density, soil organic carbon and aggregate stability are suitable indicators (indirect measures) for

assessing the hydraulic function of the soil if they respond directly to the management undergone.

Cover crops add organic carbon to the soil, contributing to increase soil aggregation and stability. They can also influence the size and distribution of pores at different depths in the soil profile, as they can contribute to increase soil porosity through the formation of biopores by plant roots (Haruna et al., 2020). This study it showed that the BS treatment had the lowest total porosity value in the first year of cultivation (Table 2). It is also possible to visualize the degradation of the soil structure that reduces the horizon (Fig. 2) due to the absence of cover crops, thus explaining the reduction in total soil porosity.

Soil loss occurs naturally and can be intensified by anthropic of land use combined with slope, but most of the annual soil loss occurs in a few intense events (rainfall) and can be amplified on bare soils. In addition, cover crops reduce the speed of water in runoff, thereby reducing water erosion (Haruna et al., 2020). This set of variables has a direct effect on soil and water losses. In this study, the treatments without cover, BS and OBS, showed the highest soil and water losses, indicating that cover crops are effective in controlling water erosion.

Grasses from spontaneous vegetation promote a faster rate of infiltration of rainfall and a greater depth when used as cover, indicating that native vegetations of this family are the most suitable type of cover for infiltrating water into the soil (Chen et al., 2020), reinforcing the water loss results found in this study in relation to the OSV and OMI treatments. The increase in erosion and reduction in soil productivity is due to the fragmentation and migration of soil aggregates caused by rain splashes (Fu et al., 2020) Under the influence of raindrops, aggregate size decreases rapidly with increasing rainfall intensity (Jiao et al., 2024), unless there is an adequate cover crop management system.

The effectiveness of soil cover crops in reducing erosion depends not only on the type and quality of plants chosen, but also on the season in which they are grown (Haruna et al., 2020), but as seen in this study, cover crops serve to protect the soil and improve its structure, and it is recommended that soil cover is maintained in a way that significantly reduces soil and water losses.

4.2 Soil chemical properties

The chemical properties of the soil were not influenced by olive tree cover crop management during the first year (Table 2), as all the treatments with the presence of olive trees exhibited higher values when compared to BS. By 2021, however, the impact of cover crop management on the soil's chemical properties became evident. A similar trend was observed for P, with the OMI treatment showing higher levels of available P (Table 2). This can be attributed to the role of cover crops in increasing total P concentrations at the soil surface, as well as their ability to absorb nutrients with low availability in the soil profile, thereby enhancing nutrient concentrations in the surface soil layers (Fageria et al., 2005; Khan et al., 2021).

4.3. Soil morphological description

The morphological description of the soil horizons under different cover crop management systems (BS, OBS, OJB, OSV, and OMI) revealed distinct variations in structure, consistency, and color, highlighting the impact of management practices on soil properties and soil horizon development. This suggests a large variation in the soil used in the experiment.

Overall, the management practices applied in each treatment influenced the degree of structural formation and horizon differentiation. The BS treatment exhibited weaker structure and lighter reddish colors. In contrast, the OJB, OSV, and OMI treatments, which incorporated cover crops and spontaneous vegetation, demonstrated stronger surface structures, darker colors, and more advanced pedogenic processes, particularly in the lower horizons. These cover crops and vegetative practices contributed to enhanced structural development and improved pedogenesis.

When the thickness of the A and transition horizons were combined, a decreasing relationship was observed in the following order and corresponding thickness: OJB (39 cm) > OSV (33 cm) > OMI (26 cm) > OBS (24 cm) > BS (9 cm). Although the OMI treatment used millet and sunn hemp as cover crops in the first two years of production, in subsequent years the treatment used herbicide to control spontaneous vegetation as a cover crop, which limited the amount of vegetable material that could contribute to the formation of the A horizon. The OJB treatment was the most effective in the development of the A horizon, exhibiting the greatest total thickness when considering the A1, A2, and transitional AB horizons, reaching approximately 39

cm. This value corresponds to twice the thickness observed in the OBS treatment and four times that recorded in the BS treatment.

The BS treatment, in addition to the low thickness of the A horizon, proved to be very shallow, as it presented the C horizon at only 42 cm, which was deeper and more distinct, associated with saprolitic material and the presence of rock fragments, justifying its definition as a Dystrudept. Cunha et al. (2019) who studied the highest parts of the Oratório stream micro-basin (Espirito Santo, Brazil), pointed out that in these regions, with predominantly mountainous to sloping relief with intense erosion, shallow or very shallow soils, such as Dystrudept, are the most common.

The majority of arable mountain soils in tropical climates fall into the Inceptisol order, which has a high silt content, blocky structure, low permeability, low *solum* thickness, associated with steeper slopes, and if not protected by vegetation cover, losses are unsustainable, reaching values of up to 339 Mg ha^{-1} $year^{-1}$ (Oliveira et al., 2024; Schick et al., 2000; Silva et al., 2009). However, it should be borne in mind that crop profiles under field conditions are influenced by numerous other variables that can have a wide range of effects, including the natural variability of the soil and the variety of conditions under which agricultural operations are carried out (Ralisch et al., 2010).

4.4. Soil micromorphological description

Maintaining the bare soil in the BS and OBS treatments resulted in a reduction in surface porosity, as shown in Figure 3, due to the impact of raindrops compacting and segregating the soil, resulting in very small particles filling the pores (Jiao et al., 2024). This morphological evidence suggests the formation of incipient compaction due to the soil degradation process, which can reduce the bioturbation benefits of soil macrofauna, which is partly responsible for the formation of pores in the soil (Canisares et al., 2020). The intensification of the cover crop sequence increases a system of secondary pores associated with the structural porosity of the soil in the first year, and as a result of this increase there are improvements in unsaturated hydraulic conductivity and pore connectivity (Villarreal et al., 2021). In this research, the cover crops chosen in the first year were more effective in improving total porosity in depth (Table 2).

In the soils thin sections (depth 0-4.3 cm) shown in Figure 3, the OSV treatment was more pronounced and the OJB treatment was virtually absent, showing a lighter color in the first 2 cm, suggesting clay migration into the lower layers. The micromorphological analysis demonstrated that the inclusion of cover crops,

particularly in the OJB and OMI systems, significantly enhanced soil development compared to bare soil and olive monoculture treatments. These systems exhibited a more advanced pedogenic process, improved structural development, and the presence of iron nodules and root fragments. The micromass in the cover crop systems reflects better organic activity. In contrast, the BS and OBS treatments showed weaker micromorphological features, with minimal pedofeatures and less structural complexity.

In general, the thin sections showed microstructure in angular blocks, with moderately to weakly separated, weakly accommodated aggregates and planar voids (fissures) between ped faces, consistent with the morphological description of the soil profile (Fig. 2). The birefringent fabric was porphyric, which means a dispersed skeleton in the matrix background of clay domains, and granostriated, i.e. the clay domains have been compacted and orientated around the grains of sand and gravel. In addition, the fabric is micaceous crystallitic, due to the presence of a large amount of mica in the fine sand and silt fraction, derived from granitic rocks.

In the OSV treatment, the micromass exhibited a speckled and crystalline structure, while the pedoforms contained concentric nodules composed of illuvial clay film fragments, highlighting the role of erosive forces in mobilizing fine soil particles. The presence of illuvial clay films suggests that erosion not only removes surface material but also redistributes clay within the profile, influencing soil microstructure properties (Table 4, Fig. 7).

5. Conclusions

1. The treatment consisting of olive trees in association with jack beans (2015/2016 and 2016/2017), followed by the maintenance of crowned and mown spontaneous vegetation (2017/2021), resulted in the lowest soil loss over six years of study. This approach promoted improvements in soil structure, as evidenced by the increase in the thickness of the A horizon and the enhancement of total porosity, indicating beneficial effects on soil conservation and quality.
2. The presence of illuvial clay film fragments underscores the influence of erosive forces in detaching and redistributing fine soil particle within the surface layer.
3. Cover crop management system exert a significant influence on the structural and microstructural modifications of the soil in a tropical Dystrudept.

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7. References

Alvares, C. A.; Stape, J. L.; Sentelhas, P. C.; Gonçalves, J. L. M.; Sparovek, G. 2014. Koppen's climate classification map for Brazil. Meteorologische Zeitschrift, Vol. 22, No. 6, 711–728. http://dx.doi.org/10.1127/0941-2948/2013/0507

Aparecido, L.E. de O., Torsoni, G.B., Lima, R.F. de, Mesquita, D.Z., Peche, P.M., 2023. Agroclimatic Mapping for Olive Cultivation in Brazil: Pinpointing Optimal Growing Regions. J Sci Food Agric. https://doi.org/10.1002/jsfa.13221

Arias-Giraldo, L.F., Guzmán, G., Montes-Borrego, M., Gramaje, D., Gómez, J.A., Landa, B.B., 2021. Going beyond soil conservation with the use of cover crops in mediterranean sloping olive orchards. Agronomy 11. https://doi.org/10.3390/agronomy11071387

Bagnall, D.K., Morgan, C.L.S., Bean, G. Mac, Liptzin, D., Cappellazzi, S.B., Cope, M., Greub, K.L.H., Rieke, E.L., Norris, C.E., Tracy, P.W., Aberle, E., Ashworth, A., Tavarez, O.B., Bary, A.I., Baumhardt, R.L., Gracia, A.B., Brainard, D.C., Brennan, J.R., Reyes, D.B., Bruhjell, D., Carlyle, C.N., Crawford, J.J.W., Creech, C.F., Culman, S.W., Deen, B., Dell, C.J., Derner, J.D., Ducey, T.F., Duiker, S.W., Dyck, M.F., Ellert, B.H., Entz, M.H., Solorio, A.E., Fonte, S.J., Fonteyne, S., Fortuna, A.M., Foster, J.L., Fultz, L.M., Gamble, A. V., Geddes, C.M., Griffin-LaHue, D., Grove, J.H., Hamilton, S.K., Hao, X., Hayden, Z.D., Honsdorf, N., Howe, J.A., Ippolito, J.A., Johnson, G.A., Kautz, M.A., Kitchen, N.R., Kumar, S., Kurtz, K.S.M., Larney, F.J., Lewis, K.L., Liebman, M., Ramirez, A.L., Machado, S., Maharjan, B., Gamiño, M.A.M., May, W.E., McClaran, M.P., McDaniel, M.D., Millar, N., Mitchell, J.P., Moore, A.D., Moore, P.A., Gutiérrez, M.M., Nelson, K.A., Omondi, E.C., Osborne, S.L., Alcalá, L.O., Owens, P., Pena-Yewtukhiw, E.M., Poffenbarger, H.J., Lira, B.P., Reeve, J.R., Reinbott, T.M., Reiter, M.S., Ritchey, E.L., Roozeboom, K.L., Rui, Y., Sadeghpour, A., Sainju, U.M., Sanford, G.R., Schillinger, W.F., Schindelbeck, R.R., Schipanski, M.E., Schlegel, A.J., Scow, K.M., Sherrod, L.A., Shober, A.L., Sidhu, S.S., Moya, E.S., St. Luce, M., Strock, J.S., Suyker, A.E., Sykes, V.R., Tao, H., Campos, A.T., Van Eerd, L.L., van Es, H.M., Verhulst, N., Vyn, T.J., Wang, Y., Watts, D.B., Wright, D.L., Zhang, T., Honeycutt, C.W., 2022. Selecting soil hydraulic properties

as indicators of soil health: Measurement response to management and site characteristics. Soil Science Society of America Journal 86, 1206–1226. https://doi.org/10.1002/saj2.20428

Beniaich, A., Guimarães, D.V., Avanzi, J.C., Silva, B.M., Acuña-Guzman, S.F., dos Santos, W.P., Silva, M.L.N., 2023. Spontaneous vegetation as an alternative to cover crops in olive orchards reduces water erosion and improves soil physical properties under tropical conditions. Agric Water Manag 279, 108186. https://doi.org/10.1016/j.agwat.2023.108186

Beniaich, A., Silva, M.L.N., Guimarães, D. V., Avalos, F.A.P., Terra, F.S., Menezes, M.D., Avanzi, J.C., Cândido, B.M., 2022. UAV-based vegetation monitoring for assessing the impact of soil loss in olive orchards in Brazil. Geoderma Regional 30. https://doi.org/10.1016/j.geodrs.2022.e00543

Borges, T.H., López, L.C., Pereira, J.A., Cabrera-Vique, C., Seiquer, I., 2017. Comparative analysis of minor bioactive constituents (CoQ10, tocopherols and phenolic compounds) in Arbequina extra virgin olive oils from Brazil and Spain. Journal of Food Composition and Analysis 63, 47–54. https://doi.org/10.1016/J.JFCA.2017.07.036

Cândido, B.M., Silva, M.L.N., Curi, N., De Freitas, D.A.F., Mincato, R.L., Ferreira, M.M., 2015. Indicator indexing methods in assessment of soil quality in relation to water erosion. Rev Bras Cienc Solo 39, 589–597. https://doi.org/10.1590/01000683rbcs20140363

Canisares, L.P., Cherubin, M.R., Silva, L.F.S. da, Franco, A.L.C., Cooper, M., Mooney, S.J., Cerri, C.E.P., 2020. Soil microstructure alterations induced by land use change for sugarcane expansion in Brazil. Soil Use Manag 36, 189–199. https://doi.org/10.1111/sum.12556

Chen, W., Li, Z., Jiao, L., Wang, C., Gao, G., Fu, B., 2020. Response of soil moisture to rainfall event in black locust plantations at different stages of restoration in hilly-gully area of the Loess Plateau, China. Chin Geogr Sci 30, 427–445. https://doi.org/10.1007/s11769-020-1121-4

Cogo, N.P., Levien, R., Schwarz, R.A., 2003. Soil and water losses by rainfall erosion influenced by tillage methods, slope-steepness classes, and soil fertility levels. Rev Bras Cienc Solo 27, 743–753. https://doi.org/10.1590/S0100-06832003000400019

Cunha, A. de M., Fontes, M.P.F., Lani, J.L., 2019. Mineralogical and chemical attributes of soils from the Brazilian atlantic forest domain. Sci Agric 76, 82–92. https://doi.org/10.1590/1678-992x-2017-0109

Dane, J.H., Topp, G.C., 2002. Methods of soil analysis: Physical methods, Part 4. ed. Soil Science Society of America, Madison.

Dantas, A.A.A., Carvalho, L.G. de, Ferreira, E., 2007. Climatic classification and tendencies in Lavras region, MG. Ciência e Agrotecnologia 31, 1862–1866. https://doi.org/10.1590/S1413-70542007000600039

Fageria, N.K., Baligar, V.C., Bailey, B.A., 2005. Role of cover crops in improving soil and row crop productivity. Commun Soil Sci Plant Anal. https://doi.org/10.1080/00103620500303939

Fu, Y., Li, G., Zheng, T., Zhao, Y., Yang, M., 2020. Fragmentation of soil aggregates induced by secondary raindrop splash erosion. Catena (Amst) 185. https://doi.org/10.1016/j.catena.2019.104342

Guimarães, D.V., Silva, M.L.N., Beiniach, A., Bispo, D.F.A., Contins, J.G.P., Curi, N., 2018. Relationship between soil organic matter fractions and cover plants in olive post planting. Rev Bras Frutic 40, 1–12. https://doi.org/10.1590/0100-29452018027

Guimarães, D.V., Silva, M.L.N., Beniaich, A., Pio, R., Gonzaga, M.I.S., Avanzi, J.C., Bispo, D.F.A., Curi, N., 2021. Dynamics and losses of soil organic matter and nutrients by water erosion in cover crop management systems in olive groves, in tropical regions. Soil Tillage Res 209. https://doi.org/10.1016/j.still.2020.104863

Haruna, S.I., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S., Gao, Y., 2020. Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences and Environment. https://doi.org/10.1002/agg2.20105

Instituto Nacional de Meteorologia - INMET. Normais climatológicas do Brasil: 1991-2020. Brasília: INMET, 2022. Disponível em: https://portal.inmet.gov.br/normais.

IUSS Working Group WRB, 2022. World reference base for soil resources: international soil classification system for naming soils and creating legends for soil maps, 4th ed. Viena.

Jiao, F., Li, G., Liu, Z., Zhang, X., 2024. Changes in the microscopic morphology and microstructure of loess pores under raindrop splash. Catena (Amst) 243. https://doi.org/10.1016/j.catena.2024.108150

Kapur, S., Ryan, J., Akça, E., Çelik, I., Pagliai, M., Tülün, Y., 2007. Influence of mediterranean cereal-based rotations on soil micromorphological characteristics. Geoderma 142, 318–324. https://doi.org/10.1016/j.geoderma.2007.08.024

Kemper, W.D., Rosenau, R.C., 1986. Aggregate Stability and Size Distribution, in: Klute, A. (Ed.), Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods, 5.1, Second Edition. pp. 425–442. https://doi.org/https://doi.org/10.2136/sssabookser5.1.2ed.c17

Khan, R., Farooque, A.A., Brown, H.C.P., Zaman, Q.U., Acharya, B., Abbas, F., McKenzie-Gopsill, A., 2021. The role of cover crop types and residue incorporation in improving soil chemical properties. Agronomy 11. https://doi.org/10.3390/agronomy11102091

Kozak, M., Piepho, H.P., 2018. What's normal anyway? Residual plots are more telling than significance tests when checking ANOVA assumptions. J Agron Crop Sci 204, 86–98. https://doi.org/10.1111/JAC.12220

Márquez-García, F., Hayas, A., Peña, A., Ordóñez-Fernández, R., González-Sánchez, E.J., 2024. Influence of cover crops and tillage on organic carbon loss in Mediterranean olive orchards. Soil Tillage Res 235. https://doi.org/10.1016/j.still.2023.105905

Melo, L.B.B. de, Silva, B.M., Peixoto, D.S., Chiarini, T.P.A., de Oliveira, G.C., Curi, N., 2021. Effect of compaction on the relationship between electrical resistivity and soil water content in Oxisol. Soil Tillage Res 208. https://doi.org/10.1016/j.still.2020.104876

Melo, L.B.B., Benevenute, P.A.N., Barbosa, S.M., Chiarini, T.P.A., Oliveira, G.C., Lima, J.M., Vanella, D., Consoli, S., Ferreira, E.A., Silva, B.M., 2023. Spatial and temporal electrical resistivity dynamics in a dense Ultisol under deep tillage and different citrus root-stocks. Soil Tillage Res 228. https://doi.org/10.1016/j.still.2022.105629

Oliveira, E.M. de, Hermógenes, G.M., Brito, L. da C., Silva, B.M., Avanzi, J.C., Beniaich, A., Silva, M.L.N., 2024. Cover crop management systems improves soil quality and mitigate water erosion in tropical olive orchards. Sci Hortic 330, 113092. https://doi.org/10.1016/J.SCIENTA.2024.113092

Peña, E.A., Slate, E.H., 2006. Global Validation of Linear Model Assumptions. J Am Stat Assoc 101, 341–354. https://doi.org/10.1198/016214505000000637

Ralisch, R., Almeida, E. de, Silva, A.P. da, Pereira Neto, O.C., Guimarães, M. de F., 2010. Morphostructural characterization of soil conventionally tilled with mechanized and animal traction with and without cover crop. Rev. Bras. Ci. Solo 34, 1795–1802. https://doi.org/10.1590/S0100-06832010000600003

Santos, R.D. dos, Santos, H.G. dos, Ker, J.C., Anjos, L.H.C. dos, Shimizu, S.H., 2015. Manual de descrição e coleta de solo no campo, 7th ed. Sociedade Brasileira de Ciência do Solo, Viçosa.

Santos, W.P. dos, Silva, M.L.N., Avanzi, J.C., Acuña-Guzman, S.F., Cândido, B.M., Cirillo, M.Â., Curi, N., 2021. Soil quality assessment using erosion-sensitive indices and fuzzy membership under different cropping systems on a Ferralsol in Brazil. Geoderma Regional 25. https://doi.org/10.1016/j.geodrs.2021.e00385

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C. dos, Oliveira, V.Á. de, Lumbreras, J.F., Coelho, M.R., Almeida, J.A. de, Araújo Filho, J.C. de, Oliveira, J.B. de, Cunha, T.J.F., 2018. Sistema brasileiro de classificação de solos, 5ª. ed. Empresa Brasileira de Pesquisa Agropecuária, Brasília, DF.

Schick, J., Bertol, I., Batistela, O., Balbinot Júnior, A.A., 2000. Water erosion in clayey inceptisol in different crop and tillage systems: I. Soil and water losses. Rev Bras Cienc Solo 24, 427–436.

Silva, A.E. da, Fontana, A., Melo, A. da S., Martins, A.L. da S., Inda, A.V., Santi, A., Madari, B.E., Mattos, B.B., Almeida, B.G. de, Alves, B.J.R., Jantalia, C.P., Pérez, D.V., Campos, D.V.B. de, Villani, E.M. de A., Martins, E. de S., Oliveira, E.M. de, Clemente, E. de P., Novotny, E.H., Bona, F.D. de, Balieiro, F. de C., Andrade, F.V., Gregoris, G., Donagemma, G.K., Valladares, G.S., Debiasi, H., Ruiz, H.A., Assis, I.R. de, Fink, J.R., João Herbert Moreira, Viana, J.H.M., Araújo Filho, J.C. de, Correa, J.C. de O., Salton, J.C., Franchini, J.C., Pires, L. de O.B., Anjos, L.H.C. dos, Hernani, L.C., Saldanha, M.F.C., Corrêa, M.M., Sá, M.A.C. de, Fontes, M.P.F., Coelho, M.R., Tomazi, M., Cooper, M., Dias Junior, M. de S., Torres, M.G., Martins, P.C.C., Soares, P.F.C., Teixeira, P.C., Freitas, P.L. de, Machado, P.L.O. de A., Fernandes, R.B.A., Cantarutti, R.B., Ralisch, R., Novais, R.F., Calderano, S.B., Castro, S.S. de, Bianchi, S.R., Bhering, S.B., Pérez, S.P.V., Dechen, S.C.F., Venegas, V.H.A., Klein, V.A., Benites, V. de M., Escaleira, V., Teixeira, W.G., Silva, W.M., 2017. Manual de métodos de análise de solo, 3rd ed. Empresa Brasileira de Pesquisa Agropecuária - Embrapa Solos, Rio de Janeiro.

Silva, A.M. da, Silva, M.L.N., Curi, N., Avanzi, J.C., Ferreira, M.M., 2009. Rainfall erosivity and erodibility of Cambisol (Inceptisol) and Latosol (Oxisol) in the region of Lavras, southern Minas Gerais state, Brazil. Rev Bras Cienc Solo 33, 1811–1820. https://doi.org/10.1590/S0100-06832009000600029

Silva, L.F.S. da, Marinho, M. de A., Matsura, E.E., Cooper, M., Ralisch, R., 2015. Morphological and micromorphological changes in the structure of a Rhodic Hapludox as a result of agricultural management. Rev Bras Cienc Solo 39, 205–221. https://doi.org/10.1590/01000683rbcs20150045

Skorupa, A.L.A., Silva, S.H.G., Poggere, G.C., Tassinari, D., Pinto, L.C., Zinn, Y.L., Curi, N., 2017. Similar soils but different soil-forming factors: converging evolution of Inceptisols in Brazil. Pedosphere 27, 747–757. https://doi.org/10.1016/S1002-0160(17)60443-0

Soil Survey Staff, 2022. Keys to soil taxonomy, 13th ed.

Stoops, G., 2003. Guidelines for analysis and description of soil and regolith thin sections, 2nd ed. Madson SSSA, Hoboken. https://doi.org/10.2136/guidelinesforanalysis2

Villarreal, R., Lozano, L.A., Melani, E.M., Polich, N.G., Salazar, M.P., Bellora, G.L., Soracco, C.G., 2021. First-year cover crop effects on the physical and hydraulic properties of the surface layer in a loamy soil. Soil Tillage Res 213. https://doi.org/10.1016/j.still.2021.105141

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

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses a guide to conservation planning. USDA, Agricultural handbook, 537.

Wrege, M.S., Coutinho, E.F., Pantano, A.P., Jorge, R.O., 2015. Potencial distribution of olive in Brazil and worldwide. Rev Bras Frutic 37, 656–666. https://doi.org/10.1590/0100-2945-174/14

Zhang, R., 1997. Infiltration models for the disk infiltrometer. Soil Science Society of America Journal 61, 1597–1603. https://doi.org/10.2136/sssaj1997.03615995006100060008x

Zuazo, V.H.D., Rodríguez, B.C., García-Tejero, I.F., Ruiz, B.G., Tavira, S.C., 2020. Benefits of organic olive rainfed systems to control soil erosion and runoff and improve soil health restoration. Agron Sustain Dev 40. https://doi.org/10.1007/s13593-020-00644-1/Published

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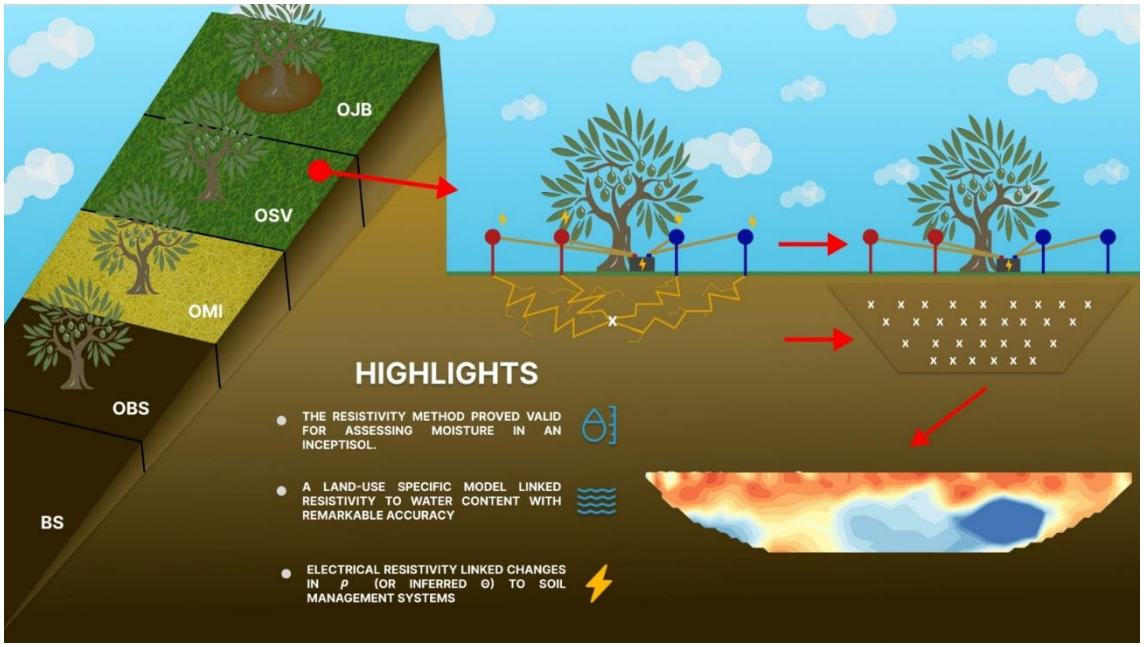
PAPER 2 – INFLUENCE OF COVER CROP MANAGEMENT ON SOIL WATER CONTENT VARIABILITY ASSESSED VIA ELECTRICAL RESISTIVITY IN OLIVE ORCHARDS

Abstract

Conservation practices in agricultural production are crucial for soils that are naturally susceptible to erosion and degradation such as shallow soils at high altitudes and in regions experiencing intense, short-duration rainfall. However, there remains a significant knowledge gap regarding the integration of the soil-plant system, soil quality and water security. To address this gap and mitigate soil and water losses, a six-year study was conducted focusing on five cover crop management systems in olive production on a tropical Dystrudept. The study assessed soil water permeability, soil and water losses using the standard erosion plot method, and electrical resistivity to estimate soil water content at 70 cm, analysing water storage across each cover crop management system. The electrical resistivity method proved to be a reliable tool for inferring the amount and distribution of soil moisture in Inceptisol in tropical regions. These evaluations enable the association of variations in electrical resistivity (ρ) – or inferred θ – with the implementation of different soil conservation management systems, thereby providing valuable insights into the complex processes affecting the soil-plant system.

Keywords: Inceptisol, geophysical technique, *Olea europaea* L., water erosion.

Graphical abstract



1. Introduction

Brazil offers suitable areas for olive (*Olea europaea* L.) cultivation, particularly in the southern region of Minas Gerais, where climate and topographical are favourable, despite the coutry's generally high temperatures (Aparecido et al., 2023; Oliveira et al., 2024; Silva et al., 2012). The interplay of high altitude and rugged terrain has resulted to the development of shallow, sandy soils characterized by high erosion rates and limited *solum* thickness (Benites et al., 2003). Soil water availability plays a crucial role in regulating crop production, as it significantly influences the biogeochemical processes occurring within the soil, highlighting its fundamental importance in agricultural practices (Blanchy et al., 2020; Melo et al., 2021).

The mitigation of soil erosion in olive cultivation is directly linked to the implementation of soil conservation practices (Oliveira et al., 2024). Water erosion and the degradation of soil structure caused by tillage can substantially affect water and nutrient availability, thereby influencing plant development and crop productivity. Conservation agriculture practices are designed to counteract these processes while promoting sustainable agricultural production (Blanchy et al., 2020; Oliveira et al., 2024). Sustainable soil management systems play a crucial role in perennial cropping system by enhancing and maintaining soil organic matter – an essential indicator of soil quality – mitigating erosion, facilitating atmospheric CO_2 sequestration, and promoting biodiversity and ecosystem stability (Celano et al., 2011).

Soil moisture determination methods are typically based on direct measurements, which involve weighing soil samples before and after oven-drying, or on *in situ* indirect techniques (Acosta et al., 2022). In recent years, indirect methods, particularly those relying on electrical properties such as electrical resistivity, have been increasingly employed for soil characterization and moisture estimation (Melo et al., 2021, 2023; Santana et al., 2023). While conventional techniques are generally limited to the rhizosphere and provide point-based measurements, electrical resistivity enables spatially continuous assessments in both horizontal and vertical directions, offering a more comprehensive representation of soil moisture distribution (Acosta et al., 2022; Melo et al., 2021).

Electrical resistivity is the most widely utilized geophysical technique for soil moisture determination and monitoring, as the physical properties of soil materials can be correlated and quantified through their geoelectrical properties (Fagbemigun et al., 2021). However, electrical resistivity is influenced by root systems and various soil

attributes, necessitating preliminary laboratory calibration as well as qualitative or quantitative data interpretations (Celano et al., 2011; Samouëlian et al., 2005). Experimental studies investigating the statistical relationship between soil moisture and electrical resistivity have led to the development of a power model for predicting soil moisture based on electrical resistivity measurements (Melo et al., 2021; Santana et al., 2023).

The main hypotheses of this study are: (i) the electrical resistivity method can provide an accurate estimation of soil water content distribution but may require site-specific calibration tailored to individual soil pedons in an Inceptisol, and (ii) the spatial variability of soil water content may be influenced by cover crop systems. Therefore, this research aimed to model the relationship between soil water content and electrical resistivity in a Dystrudept under tropical conditions and to assess the impact of cover crop management in olive orchards on soil water content and electrical resistivity across different landscapes position.

2. Material and Methods

2.1 Study site

The research was conducted in the experimental area of the Federal University of Lavras (Lavras, Minas Gerais, Brazil, 21º13’20” S and 44º58’17” W), from March 2015 to September 2021, during six hydrological years. The experimental site is at an altitude 918 m a.s.l., on a slope of 23% (Fig. 1). The climate is classified as subtropical highland (Cwb) according to Köppen Climate Classification System (Alvares et al., 2014), with a mean annual rainfall of 1,383.4 mm and a mean annual temperature of 20.6 ºC (INMET, 2022). Winters are dry and cool, whereas summers are characterised by higher rainfall and daily average temperatures exceeding 22 ºC (Dantas et al., 2007). Information on rainfall and maximum and minimum temperatures are shown in Fig. 2, the data were obtained from a weather station located at the Federal University of Lavras. The soil in the study area was classified as Cambissolo Háplico Tb Distrófico according to the Brazilian Soil Classification System (Santos et al., 2018), which corresponds to Dystrudept in Soil Taxonomy (Soil Survey Staff, 2022), and to Dystric Cambisol in WRB (IUSS Working Group WRB, 2022). The values of the physical and chemical attributes used are described in Table 1.

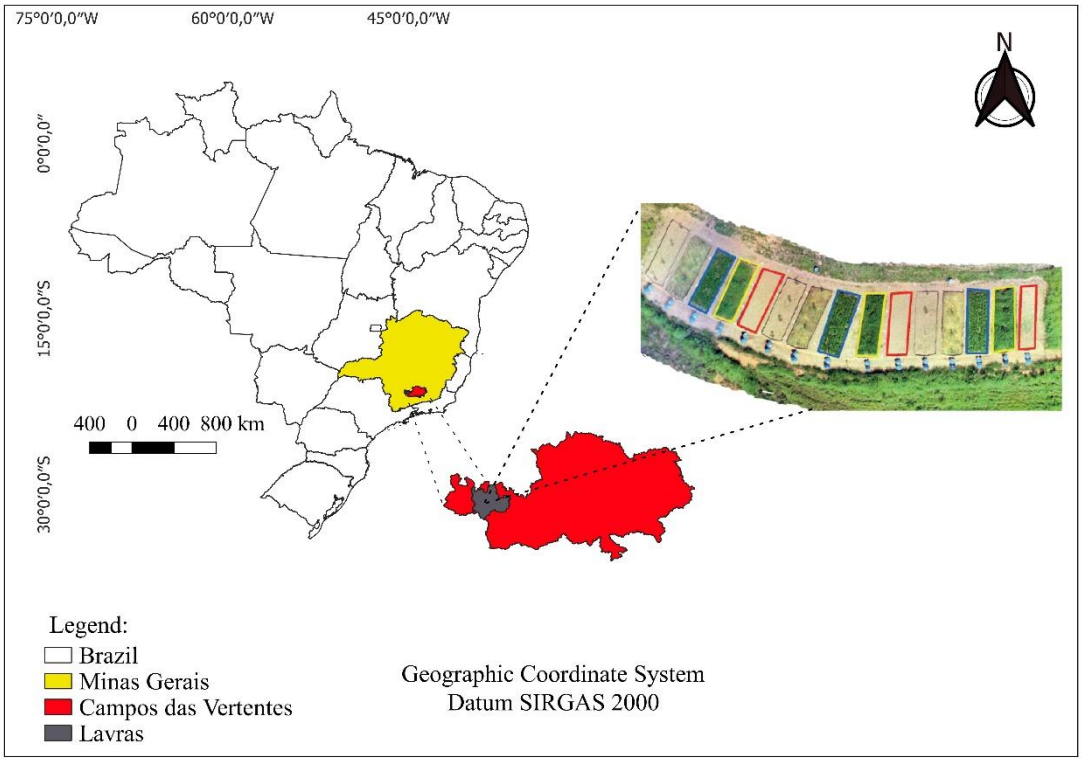


Fig. 1. Location of the experimental area (Lavras, Minas Gerais, Brazil).

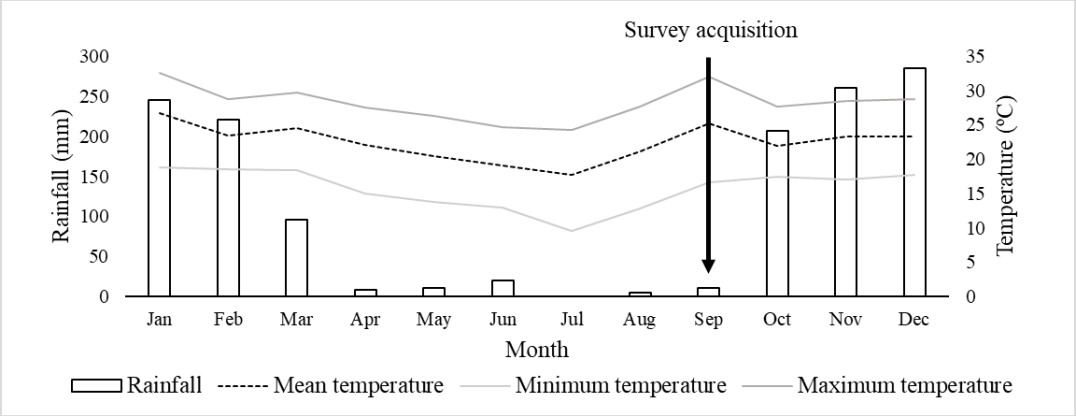


Fig. 2. Precipitation of the experimental area in Lavras, Minas Gerais, Brazil. The black arrow indicates the timing of the electrical resistivity acquisitions.

2.2 Experimental design

The experimental study has been running since March 2015, when the olive plantation of the 'Arbequina' cultivar was established, with a spacing of 4 m between plants and 5 m between rows along the maximum slope direction (Oliveira et al., 2024). Olive fertilization was applied following the recommendation. In the olive plantation, we applied 100 g of limestone, 20 liters of manure, 500 g of single superphosphate, and 200 g potassium chloride to each tree planting hole. For the annual fertilization in the 2015/2016 season, we applied 50 g of ammonium sulfate to each tree in November,

December, and January. For the annual fertilization in the 2016/2017 season, we applied 100 g of ammonium sulfate, 50 g potassium chloride, and 20 g of boric acid to each tree in October. We applied 100 g ammonium sulfate, 50 g potassium chloride to each tree in December. In January, we applied 100 g ammonium sulfate to each tree. During the dry season, we manually watered the olive plantation to meet the plants' water demands.

Table 1. Physical and chemical properties of Dystrudept under different cover crop management systems in an olive orchard in Lavras, Minas Gerais, Brazil.

Attributes	Treatments				
	BS	**OBS**	**OJB**	**OSV**	**OMI**
Sand (g kg^{-1})	425	380	390	350	375
Silt (g kg^{-1})	200	185	230	220	225
Clay (g kg^{-1})	375	435	380	430	400
GMD (mm)	4.31	4.24	4.84	4.52	4.71
Ks (mm h^{-1})	30.34	35.90	56.39	58.98	36.33
TP (cm^3 cm^{-3})	0.47	0.44	0.52	0.50	0.52
MaP (cm^3 cm^{-3})	0.18	0.18	0.18	0.16	0.18
MiP (cm^3 cm^{-3})	0.29	0.25	0.34	0.34	0.34
Bd (g cm^{-3})	1.20	1.26	1.26	1.20	1.35
SOM (g kg^{-1})	16.8	16.8	27.7	26.6	23.3
SB ($cmol_c$ dm^{-3})	2.21	2.91	4.21	3.97	3.12
t ($cmol_c$ dm^{-3})	2.52	3.03	4.30	4.06	3.24
m (%)	12.92	4.10	1.97	1.91	3.56
pH	4.98	5.03	5.57	5.63	5.18

GMD: geometric mean diameter (aggregate stability); Ks: unsaturated soil hydraulic conductivity; TP: total porosity; MaP: macroporosity; MiP: microporosity; Bd: bulk density; SOM: soil organic matter; SB: sum of bases; t: effective cation exchange capacity, m: aluminum saturation percentage; BS: bare soil in 2015-2021; OBS: olive tree on bare soil in 2015-2021; OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021; OMI: olive tree intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021. Sand, silt and clay: bouyoucos method; GMD: yoder type sieves immersed in water; Ks: minidisk infiltrometer; TP, MaP, MiP and Bd: undisturbed soil samples (volumetric cylinder); SOM: oxidation with $Na_2Cr_2O_7 4N + H_2SO_4 10N$; SB: Ca (extractor – KCl 1mol L^{-1}) + Mg (extractor – KCl 1mol L^{-1}) + K (extractor – Mehlich 1); t: SB + Al (extractor – KCl 1mol L^{-1}); m: Al t^{-1}; pH: in water.

The experimental design comprised five treatments (soil management systems) with three replicates arranged in a completely randomised block design. The treatments were as follows (Table 2):

1. BS – Soil maintained free of weeds and vegetation through chemical weed control and manual weeding.
2. OBS – Olive trees planted in bare soil.
3. OJB – Olive trees associated with jack bean (*Canavalia ensiformis* L.) from 2015 to 2017, followed by olive trees crowned canopies associated with mown spontaneous vegetation from 2017 to 2021.

4. OMI – Olive trees associated with a crop succession: pearl millet (*Pennisetum glaucum* L.) in 2015/2016, sunn hemp (*Crotalaria juncea* L.) in 2016/2017, and spontaneous vegetation managed with herbicide from 2017 to 2021.
5. OSV – Olive trees associated with mown spontaneous vegetation.

Table 2. Description of five study treatments.

Treatment	2015/2016	2016/2017	2017/2021
BS	----------Bare soil without olive trees----------		
OBS	----------Olive trees on bare soil----------		
OJB	---Jack beans---	--Jack beans--	-Spontaneous vegetation – crowned and mowed--
OSV	----------Spontaneous vegetation – mowed----------		
OMI	-----Millet-----	---Sunn hemp---	--------Spontaneous vegetation - herbicide---------

The spontaneous vegetation recorded in 2016 and 2017 primarily consisted of grasses, with *Brachiaria decumbens* Stapf as the dominant species, followed by *Digitaria sanguinalis* L., *Melinis minutiflora* P. Beauv., and *Eleusine indica* L.. Additionally, several broadleaf species were identified, including *Euphorbia heterophylla* L., *Amaranthus viridis* L., *Emilia fosbergii* Nicolson, *Ipomoea acuminata* Roem., *Conyza bonariensis* L., *Oxalis corniculata* L., and *Bidens pilosa* L.. In 2021, a subsequent survey was carried out, with the main dominant species found being *Brachiaria decumbens* Stapf and *Desmodium incanum* DC., and in a smaller proportion, *Amaranthus viridis* L., *Bidens pilosa* L., *Emilia fosbergii* Nicolson, and some species of *Vernonia polyanthes* (Spreng.) Less. were also recorded.

Cover crops (jack beans, millet and sunn hemp) was manually seeded at the beginning of the rainy season (November 2015 and 2016). In the jack bean, the furrows were spaced at every 50 cm in a density of eight seeds m^{-1}. In the millet and sunn hemp treatments, the spacing used was 25 cm with densities of 90 and 40 seeds m^{-1}, respectively. Regarding the fertilization of the cover cover crops, 500 kg ha^{-1} of NPK (8:28:16), in the first year and 250 kg ha^{-1} of NPK (8:28:16), in the second crop season, were applied. For chemical weed control in BS, OBS and OMI plots, glyphosate was used.

2.3 Unsaturated soil hydraulic conductivity, water erosion and soil profile horizons surveys

In 2021, unsaturated soil hydraulic conductivity was measured on a 1.0 m x 1.0 m grid within each treatment, with 48 measurements per experimental unit. There

measurements were futher classified into three positions within the plot – upper, middle and lower – each comprising 12 measurements. Data were collected using a mini-disk infiltrometer, which estimates the hydraulic conductivity of the substrate on which it is placed. A suction of 0.5 cm was applied, considering the soil's clay content of approximately 40% (Table 1), which limits infiltration. Measurements were recorded every 30 seconds until 15 to 20 mL of water had infiltrated into the soil (Zhang, 1997).

In 2021, soil and water losses were assessed using standard plots, modified in size to 12 m in length and 4 m in width (Wischmeier and Smith, 1978). The mean slope of the plots was 0.23 m m^{-1}. Runoff and sediment collection were conducted after each erosion event using two 250 L tanks installed at the lower end of each plot (Cogo et al., 2003). The first tank was connected to the second via a Geib-type splinter with nine inlet openings, ensuring that once the first tank reached full capacity, 1/9 of the runoff volume would was directed into the second tank.

A soil profile was sampled in each treatment to further characterise the effects of the cover crop management system. Sampling was conducted at the centre of the plot, down to a depth of 0-60 cm, for horizons classification (Santos et al., 2015).

2.4 Electrical resistivity surveys

2.4.1 Description of electrical resistivity measurements

Electrical resistivity (ρ) was measured in the study treatments in September 2021. The measurements aimed to assess volumetric soil moisture throughout the profile and, consequently, water storage as influenced by cover crop management in the olive orchard.

The ρ was directly measured using the X5xtal 250 Resistivity Meter (Auto Energia, Alvinópolis, MG, Brazil) with two multimeters configured in a dipole-dipole arrangement (A-B-M-N), where A-B served as the current electrodes and M-N as the potential electrodes (Samouëlian et al., 2005). Measurements were taken along a 4 m horizontal transect, with an electrode spacing of 0.19 m. The assessed depth ranged from 0 to 0.70 m, with a total of 189 measurements performed in triplicate at three landscape positions within the plot (upper, middle and lower). Consequently, ρ was calculated using Equations (1) and (2):

$$\rho = \frac{(K \times \Delta V)}{I}, \quad \text{(Eq. 1)}$$

$$K = 2\pi a, \quad \text{(Eq. 2)}$$

where ρ is electrical resistivity (Ωm); K is geometric coefficient; ΔV is potential difference (mV); I is injected electrical current (mA); and a is spacing between electrodes (m).

2.4.2 Description of ρ-θ Calibration Test

To model the ρ-θ relationship, a calibration test was conducted using undisturbed soil sampled collected *in situ* with rigid polyvinyl chloride (PVC) cylinders, each measuring 10 cm in both diameter and height (Melo et al., 2023). One undisturbed soil sample was taken from each cover crop management system treatment at a depth of 0-10 cm.

In the laboratory, a Wenner electrode arrangement (A-M-N-B) (Samouëlian et al., 2005) was employed, using aluminum electrodes spaced 0.019 m apart and inserted to a depth of 0.05 m to determine ρ. Each soil sample was saturated by capillarity for 48 hours, after which a series of ρ measurements was recorded. Simultaneously, volumetric water content (θ) was determined from the PVC soil sample weight, based on gravimetric water content and bulk density measurements. The soil water saturation process was monitored for 25 days using an X5xtal 250 Resistivity Meter (Auto Energia, Alvinópolis, MG, Brazil). The electrical conductivity of water was assumed constant throughout the measurements process. Soil samples were subsequently oven-dried at 105-110 ºC for 48 hours to determine gravimetric water content (w) and bulk density (BD) (Dane and Topp, 2002). The value of θ was then calculated using Equation (3):

$$\theta = w \left(\frac{BD}{Dw}\right), \quad \text{(Eq. 3)}$$

where θ is volumetric soil water content ($m^3\ m^{3-}$); w is the gravimetric water content (kg kg^{-1}); BD is the bulk density (Mg m^{-3}); and Dw is the density of water, assumed to be 1 Mg m^{-3}).

To estimate θ from ρ data, the ρ-θ relationship was modelled for each soil type using the power function in Equation (4):

$$\theta = a\ \rho^b, \quad \text{(Eq. 4)}$$

Where a and b are dimensionless fitting parameters.

2.5 Statistical analysis

The assumptions of normality, heteroscedasticity and variance homogeneity for the unsaturated soil hydraulic conductivity, as well as soil and water loss data, were

assessed using linear models. Graphical visualisation techniques (Kozak and Piepho, 2018) and numerical tests (Peña and Slate, 2006) were employed for evaluation. When necessary, logarithmic transformations or outlier removal methods were applied.

Once all data met the premises, an analysis of variance (ANOVA) was conducted, considering a design with five treatments (cover crop management systems) and three randomized blocks, using the F test ($P < 0.05$). When the null hypothesis of ANOVA was rejected, multiple comparisons were performed using the Tukey's test ($P < 0.05$) to identify significant differences among means.

To assess the accuracy of the ρ-θ models for each treatment, the coefficient of determination (R^2) and the root mean square error (RMSE) were calculated by comparing the observed and predicted θ values. The calibration models were evaluated using the R statistical environment (version 3.6.1) (RStudio Team, 2024).

To analyse the spatial and in-depht variability of electrical resistivity (ρ), an inversion process was performed using RES2Dinvx64 software (Geotomo Software, version 4.08). Two-dimensional (2D) resistivity images were then generated using Surfer version 13.5.583 (Golden Software). The triangulation method was applied to interpolate the ρ data points and produced 2D tomograms for each treatment.

3. Results

3.1 Survey of unsaturated soil hydraulic conductivity, water erosion and soil profile horizons

The unsaturated soil hydraulic conductivity and water erosion data are presented in Table 3. The values of unsaturated soil hydraulic conductivity measured in the upper and lower sections of the landscape were unaffected by the soil cover crop management systems. In constrast, in the central part of the landscape, soil cover crop treatments exhibited significantly higher soil water permeability, with the OJB and OSV treatments facilitating at least double the water infiltration into the soil compared to the bare soil, OBS, and BS treatments.

The use of cover crops mitigated water erosion. Regarding of water loss, only the OMI treatment was effective in reducing water erosion, with an average value of 3.23 mm $period^{-1}$. In terms of soil loss, all treatments incorporating a cover crop management system proved effective in reducing soil loss, listed in decreasing order of effectiveness: OJB > OSV, OMI > OBS, BS.

Table 3. Unsaturated soil hydraulic conductivity at three landscape of the plot positions (upper, middle and lower) and water erosion of Dystrudept under different cover crop management systems in olive tree in 2021, Lavras, Minas Gerais, Brazil.

	BS	OBS	OJB	OSV	OMI
			Unsaturated soil hydraulic conductivity (mm h^{-1})		
Upper	31.7^{ns}	33.9^{ns}	44.6^{ns}	38.8^{ns}	27.7^{ns}
Middle	29.2 b	35.6 b	67.6 a	66.2 a	48.3 ab
Lower	34.0^{ns}	41.9^{ns}	61.2^{ns}	44.2^{ns}	44.3^{ns}
			Water loss (mm $period^{-1}$)		
	39.7 a	34.0 a	39.7 a	39.2 a	3.23 b
			Soil loss (Mg ha^{-1} $period^{-1}$)		
	6.9 a	55.5 a	0.1 c	0.4 bc	0.4 bc

BS: bare soil in 2015-2021; OBS: olive tree on bare soil in 2015-2021; OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021; OMI: olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021.

The soil horizons profiles are presented in Fig 3. The treatments with maintained cover crops exhibited a preserved A horizon greater than 10 cm in depth, in contrast to the bare soil treatments, OBS and BS, which had A horizons of 7 cm and 9 cm, respectively. The treatments are listed in descending order of A horizon thickness: OJB > OSV, OMI > BS > OBS. A C horizon was found in the BS treatment, beginning at a depth of 40 cm, containing saprolitic material and gravel.

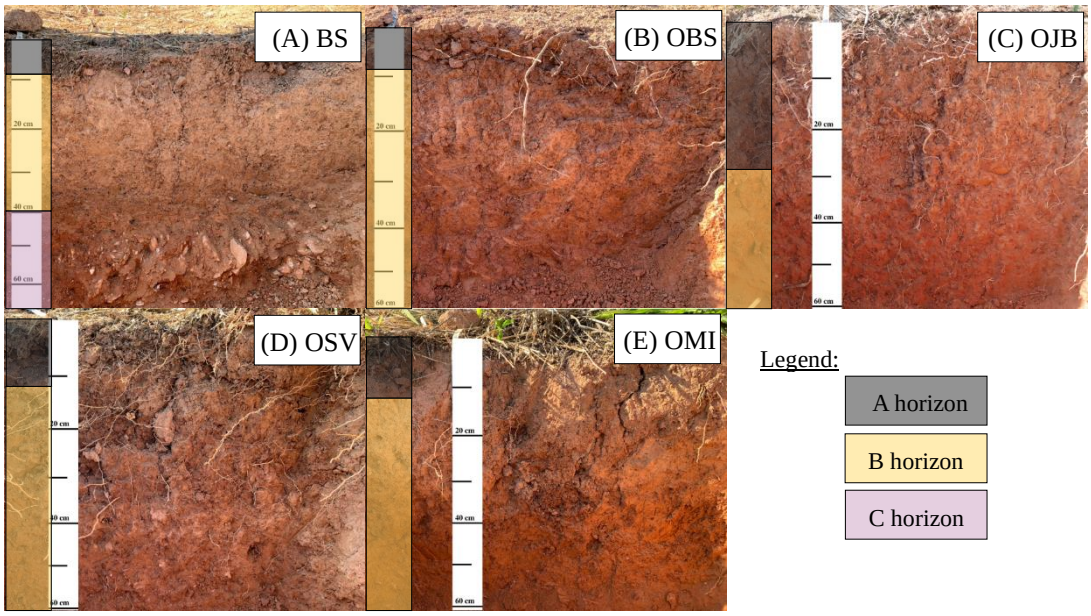


Fig. 3. Soil horizons: (A) BS - bare soil in 2015-2021 and fallow land in 2021-2023; (B) OBS - olive tree on bare soil in 2015-2021 and fallow land in 2021-2023; (C) OJB - intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021, and fallow land in 2021-2023; (D) OSV - olive tree intercropped with mowed spontaneous vegetation in 2015-2021 and fallow land in 2021-2023; (E) OMI - olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021, and fallow land in 2021-2023.

3.2 ρ-θ modelling

Fig. 4 illustrates the ρ-θ modelling, with the corresponding fitted parameters and accuracy provided in Table 4. A power model was fitted for each cover crop management system, demonstrating good accuracy with R^2 values between 0.69 to 0.93, low RMSE values between 0.027 and 0.066 m^3 m^{-3}. Consequently, the calibration of the field-measured data was carried out using the power model and the respective parameters of the empirical fitting equation.

In Fig. 3, all treatments exhibited differences in A horizon depth. As a result, the equations were not grouped, and the analyses were conducted using the specific model adjusted for each soil management system. These results indicate that the soil management system influenced the pattern of the ρ-θ ratio.

Fig 4. shows the ρ-θ relationship, emphasising the power law relationship obtained in the laboratory for values greater than 15,000 Ω m under dry soil conditions.

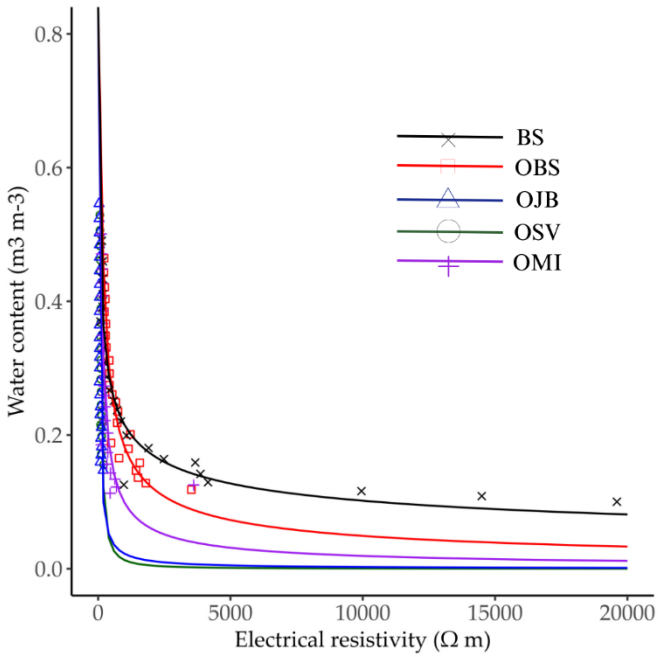


Fig. 4. ρ-θ modeling calibration curves (lines) for Dystrudept and its observed data. BS: bare soil in 2016, 2017 and 2021; OBS: olive tree on bare soil in 2016, 2017 and 2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2016, 2017 and 2021; OJB: intercropped with jack beans in 2016 and 2017, and olive tree crowned intercropped with mowed spontaneous vegetation in 2021; OMI: olive trees intercropped with millet in 2016, olive trees intercropped with sunn hemp in 2017, and olive trees with spontaneous vegetation treated with herbicide in 2021.

Table 4. Parameters and accuracies of the ρ-θ power model.

Cover crop management	a	b	RMSE	MAE	R^2
BS	2.03039	-0.3249	0.0413	0.0283	0.88
OBS	9.19520	-0.5679	0.0273	0.0203	0.93
OMI	13.3007	-0.7099	0.0661	0.0305	0.69
OSV	194.1200	-1.3916	0.0542	0.0436	0.76
OJB	13.2577	-0.9235	0.0594	0.0485	0.76

RMSE = root mean square error, MAE = mean absolute error. BS: bare soil in 2015-2021; OBS: olive tree on bare soil in 2015-2021; OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021; OMI: olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021.

3.3 Resistivity and water content distribution

Fig. 5 shows the spatial distribution of ρ estimated for each cover crop management systems, respectively. In general, higher ρ values (>1,000 Ω m) were observed.

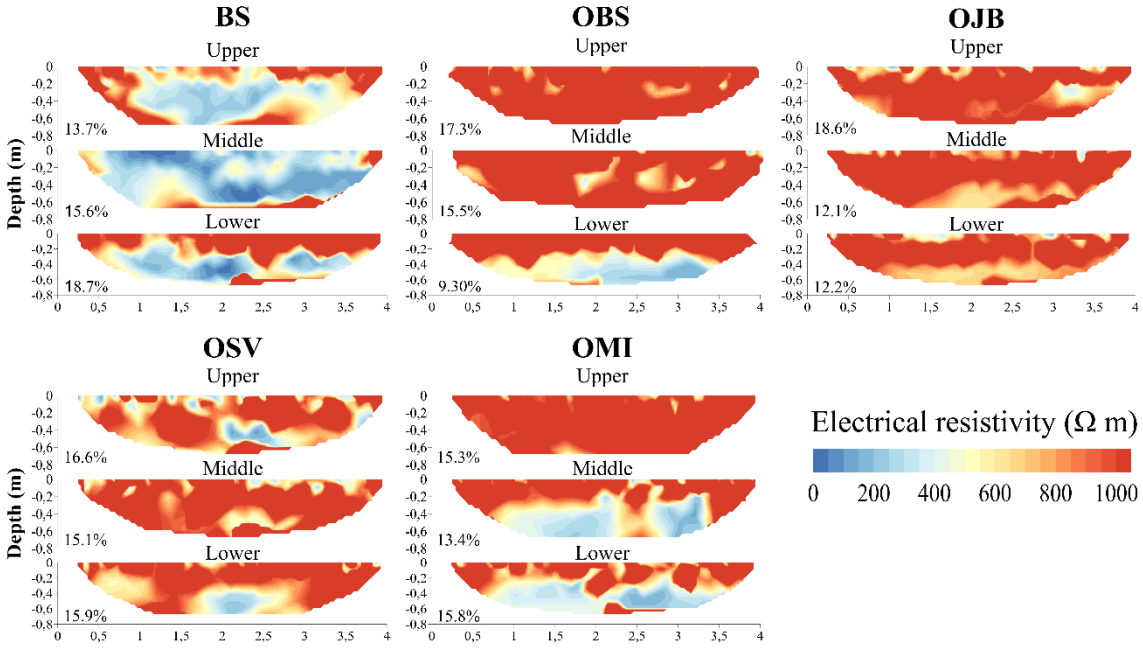


Fig. 5. The measured spatial distribution of electrical resistivity for the Dystrudept at three landscape positions of the plot (upper, middle and lower) under different cover crop management systems for olive trees in 2021, Lavras, Minas Gerais, Brazil. The absolute error, indicated by the percentages on the lower left side, represents the absolute error after the data inversion for each condition. BS: bare soil in 2015-2021; OBS: olive tree on bare soil in 2015-2021; OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021; OMI: olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021.

Fig. 6 shows the estimated θ patterns observed along the soil profile for each treatment. There is a predominance of lower θ values in the OJB and OSV treatments

across all three landscape positions of the plot. The OMI treatment is the only cover crop management system that displayed notable θ values in the middle and lower parts of the landscape of the plot. In contrast, the bare soil treatments, OBS and BS, exhibited higher θ values, particularly in the lower portion of the landscape, with values exceeding 0.4 m^3 m^{-3}.

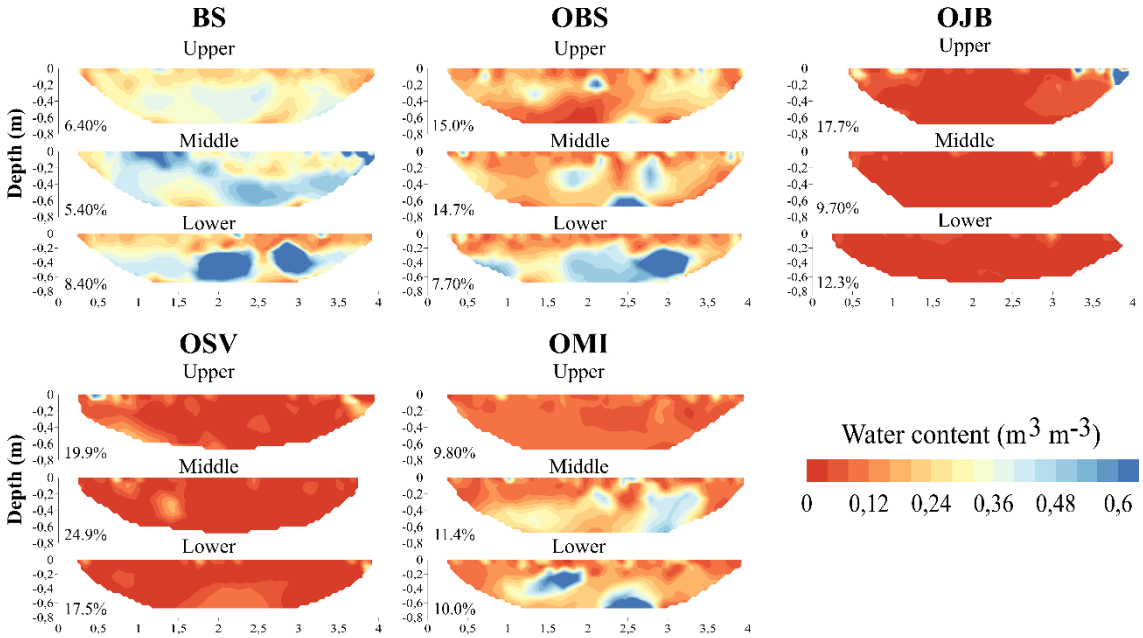


Fig. 6. Estimated soil water content (m^3 m^{-3}) for the Dystrudept at three landscape positions (upper, middle and lower) under different cover crop management systems for olive trees in 2021, Lavras, Minas Gerais, Brazil. The absolute error, indicated by the percentages on the lower left side, represents the absolute error after the data inversion for each condition. BS: bare soil in 2015-2021; OBS: olive tree on bare soil in 2015-2021; OJB: olive tree intercropped with jack beans in 2015-2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017-2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2015-2021; OMI: olive trees intercropped with millet in 2015-2016, olive trees intercropped with sunn hemp in 2016-2017, olive trees with spontaneous vegetation treated with herbicide in 2017-2021.

4. Discussion

In absolute terms, translating geophysical properties into soil water content is challenging due to the typically non-linear relationships that arise from the complex interactions between soil evaporation, root water uptake, and soil water redistribution (Vanella et al., 2023). For this reason, one of the hypotheses explored in this research is that estimating soil water content through resistivity requires specific calibration that accounts for land use factors, such as cover crop management systems. Accordingly, in

this study, ρ-θ calibrations were performed for each treatment to enhance the accuracy of θ estimates.

The good fit of the power model to represent the ρ-θ relationship is consistent with the findings of Silva et al. (2023) and Santana et al. (2023). The power model follows the same form as the analytical solution of the semi-empirical ρ-θ relationship, known as 'Archie's law' (Archie, 1942). However, this model is not suitable for clay soils (Silva et al., 2023), as electrical resistivity is influenced by several soil properties, including texture, moisture, and salinity (Samouëlian et al., 2005). While it is well established that soil moisture and electrical resistivity exhibit non-linear and inverse mathematical relationships, soil texture plays a crucial role in improving the adjustment of this relationship (Santana et al., 2023).

Based on the RMSE and R^2 values obtained, the models with the best fit were, in descending order: OBS > BS > OJB, OSV > OMI. The range of R^2 and RMSE values was higher than those reported by Santana et al. (2023), who observed R^2 values around 0.79 and RMSE values of 0.051 m^3 m^{-3} for a Typic Dystrudept in a tropical zone, with the exception of the OMI treatment, which showed a RMSE close to, but slightly higher than, 0.0661 m^3 m^{-3}.

Figure 5 shows the electrical resistivity measurements taken for each of the soil cover crop management systems. In general, the measurements from the treatments involving the presence of olive trees – OJB, OSV, OMI and OBS – revealed large areas of high resistivity, indicating significant water extraction from the soil at the studied depth studied, up to 70 cm. In the middle and lower parts of the OMI treatment, the lower section of the OBS treatment, and across all positions in the landscape for the BS treatment, a series of low resistivity values were observed, suggesting water retention in these transects. The low electrical resistivity values could be associated with the age of the olive plants. Older plants, with larger root biomass, are likely to contribute to a greater accumulation of soil porosity compared to younger plants. Therefore, studies considering different plant ages should be conducted to better understand their influence (Vanella et al., 2023).

The management systems that included cover crops demonstrated greater drainage, particularly the OJB and OSV treatments, as evidenced by the low soil moisture content observed in all three landscape positions (Fig. 6), the higher hydraulic conductivity values (Table 2), and the higher water loss values (Table 2). These factors resulted in low water storage in the soil profile, extending to at least 70 cm. Another

consideration is the water demand of the cover crops, which is particularly high during winter months. Although the OMI treatment also incorporated a cover crop, water retention was observed in the middle and lower parts of the landscape, likely due to the treatment's efficiency in reducing rainfall infiltration through water loss (Table 2).

The treatments without soil cover, OBS and BS, exhibited low hydraulic conductivity, particularly in the middle of the landscape (Table 2), resulting in water retention (Fig. 6). Results like these suggest that factors such as crop type, cover crop, topography, rainfall characteristics, and their interactions are key determinants of soil moisture response (Jin et al. 2018). In this study, the variability of the soil in the experimental area may also contribute to water retention, as crop profiles under field conditions are influenced by numerous variables. These include the natural variability of the soil and the diverse conditions under which agricultural operations are conducted, which can have a wide range of effects (Ralisch et al., 2010).

The BS treatment has another characteristic that promotes water retention in the profile: the presence of the C horizon (Fig. 3), which is less influenced by pedogenetic processes due to the presence of saprolite and unconsolidated rock material (Santos et al., 2015). Additionally, this horizon exhibits a more continuous pore distribution and tends to drain less water through macropores under lower tension (Ferreira et al., 2021).

5. Conclusion

1. The electrical resistivity method applied to the experimental area proved to be a reliable tool for inferring the quantity and distribution of soil moisture in a tropical Inceptisol.
2. A calibration model specific to each land use was developed to establish a correlation between electrical resistivity and soil water content. The models demonstrated exceptional accuracy, offering a robust estimating of soil water content.
3. The electrical resistivity evaluations enable the association of variations in ρ (or inferred θ) with the implementation of different soil conservation management systems, thereby providing valuable insights the complex processes influencing the soil-plant system.

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7. References

Acosta, J.A., Gabarrón, M., Martínez-segura, M., Martínez-martínez, S., Faz, Á., Pérez-pastor, A., Gómez-lópez, M.D., Zornoza, R., 2022. Soil Water Content Prediction Using Electrical Resistivity Tomography (ERT) in Mediterranean Tree Orchard Soils. Sensors 22. https://doi.org/10.3390/s22041365

Alvares, C. A.; Stape, J. L.; Sentelhas, P. C.; Gonçalves, J. L. M.; Sparovek, G. 2014. Koppen's climate classification map for Brazil. Meteorologische Zeitschrift, Vol. 22, No. 6, 711–728. http://dx.doi.org/10.1127/0941-2948/2013/0507

Aparecido, L.E. de O., Torsoni, G.B., Lima, R.F. de, Mesquita, D.Z., Peche, P.M., 2023. Agroclimatic Mapping for Olive Cultivation in Brazil: Pinpointing Optimal Growing Regions. J Sci Food Agric. https://doi.org/10.1002/jsfa.13221

Archie, G.E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of the AIME 146, 54–62.

Benites, V. de M., Caiafa, A.N., Mendonça, E. de S., Schaefer, C.E., Ker, J.C., 2003. Soil and vegetation on the high altitude rocky complexes of the Mantiqueira and Espinhaço mountain. Floresta e Ambiente 10, 76–85.

Blanchy, G., Watts, C.W., Richards, J., Bussell, J., Huntenburg, K., Sparkes, D.L., Stalham, M., Hawkesford, M.J., Whalley, W.R., Binley, A., 2020. Time-lapse geophysical assessment of agricultural practices on soil moisture dynamics. Vadose Zone Journal 19. https://doi.org/10.1002/vzj2.20080

Celano, G., Palese, A.M., Ciucci, A., Martorella, E., Vignozzi, N., Xiloyannis, C., 2011. Evaluation of soil water content in tilled and cover-cropped olive orchards by the geoelectrical technique. Geoderma 163, 163–170. https://doi.org/10.1016/j.geoderma.2011.03.012

Cogo, N.P., Levien, R., Schwarz, R.A., 2003. Soil and water losses by rainfall erosion influenced by tillage methods, slope-steepness classes, and soil fertility levels. Rev Bras Cienc Solo 27, 743–753. https://doi.org/10.1590/S0100-06832003000400019

Dane, J.H., Topp, G.C., 2002. Methods of soil analysis: Physical methods, Part 4. ed. Soil Science Society of America, Madison.

Dantas, A.A.A., Carvalho, L.G. de, Ferreira, E., 2007. Climatic classification and tendencies in Lavras region, MG. Ciência e Agrotecnologia 31, 1862–1866. https://doi.org/10.1590/S1413-70542007000600039

Fagbemigun, S.T., Oyebamiji, R.A., Faloyo, I.J., Arowoogun, I.K., Amosun, O.J., Sanuade, A.O., 2021. Integration of electrical resistivity and soil analysis for agricultural soil characterization-a case study. Arabian Journal of Geosciences 14. https://doi.org/10.1007/s12517-021-06772-6/Published

Ferreira, Q. de C.G., Bacellar, L. de A.P., Viana, J.H.M., 2021. Evaluation of soil moisture by electrical resistivity in Oxisols of the central Brazilian savanna. Geoderma Regional 26. https://doi.org/10.1016/j.geodrs.2021.e00408

Instituto Nacional de Meteorologia - INMET. Normais climatológicas do Brasil: 1991-2020. Brasília: INMET, 2022. Disponível em: https://portal.inmet.gov.br/normais.

IUSS Working Group WRB, 2022. World reference base for soil resources: international soil classification system for naming soils and creating legends for soil maps, 4th ed. Viena.

Jin, Z., Guo, L., Lin, H., Wang, Y., Yu, Y., Chu, G., Zhang, J., 2018. Soil moisture response to rainfall on the Chinese Loess Plateau after a long-term vegetation rehabilitation. Hydrol Process 32, 1738–1754. https://doi.org/10.1002/hyp.13143

Kozak, M., Piepho, H.P., 2018. What's normal anyway? Residual plots are more telling than significance tests when checking ANOVA assumptions. J Agron Crop Sci 204, 86–98. https://doi.org/10.1111/JAC.12220

Melo, L.B.B. de, Silva, B.M., Peixoto, D.S., Chiarini, T.P.A., de Oliveira, G.C., Curi, N., 2021. Effect of compaction on the relationship between electrical resistivity and soil water content in Oxisol. Soil Tillage Res 208. https://doi.org/10.1016/j.still.2020.104876

Melo, L.B.B., Benevenute, P.A.N., Barbosa, S.M., Chiarini, T.P.A., Oliveira, G.C., Lima, J.M., Vanella, D., Consoli, S., Ferreira, E.A., Silva, B.M., 2023. Spatial and temporal electrical resistivity dynamics in a dense Ultisol under deep tillage and different citrus root-stocks. Soil Tillage Res 228. https://doi.org/10.1016/j.still.2022.105629

Oliveira, E.M. de, Hermógenes, G.M., Brito, L. da C., Silva, B.M., Avanzi, J.C., Beniaich, A., Silva, M.L.N., 2024. Cover crop management systems improves soil quality and mitigate water erosion in tropical olive orchards. Sci Hortic 330, 113092. https://doi.org/10.1016/J.SCIENTA.2024.113092

Peña, E.A., Slate, E.H., 2006. Global Validation of Linear Model Assumptions. J Am Stat Assoc 101, 341–354. https://doi.org/10.1198/016214505000000637

Ralisch, R., Almeida, E. de, Silva, A.P. da, Pereira Neto, O.C., Guimarães, M. de F., 2010. Morphostructural characterization of soil conventionally tilled with mechanized and animal traction with and without cover crop. Rev. Bras. Ci. Solo 34, 1795–1802. https://doi.org/10.1590/S0100-06832010000600003

RStudio Team, 2024. RStudio: integrated development environment for R. [WWW Document]. URL https://posit.co/download/rstudio-desktop/ (accessed 2.15.24).

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., Richard, G., 2005. Electrical resistivity survey in soil science: A review. Soil Tillage Res. https://doi.org/10.1016/j.still.2004.10.004

Santana, M.L.T., Faria, V.L. de, Barbosa, S.M., Serafim, M.E., Uezu, A., Silva, B.M., Avanzi, J.C., 2023. Impacts of Land Use Changes on Soil Functions and Water Security: Insights from a Three-Year-Long Study in the Cantareira System, Southeast of Brazil. Sustainability 15, 13395. https://doi.org/10.3390/su151813395

Santos, R.D. dos, Santos, H.G. dos, Ker, J.C., Anjos, L.H.C. dos, Shimizu, S.H., 2015. Manual de descrição e coleta de solo no campo, 7th ed. Sociedade Brasileira de Ciência do Solo, Viçosa.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C. dos, Oliveira, V.Á. de, Lumbreras, J.F., Coelho, M.R., Almeida, J.A. de, Araújo Filho, J.C. de, Oliveira, J.B. de, Cunha, T.J.F., 2018. Sistema brasileiro de classificação de solos, 5a. ed. Empresa Brasileira de Pesquisa Agropecuária, Brasília, DF.

Silva, L. de C.M. da, Peixoto, D.S., Azevedo, R.P., Avanzi, J.C., Dias Junior, M. de S., Vanella, D., Consoli, S., Acuña-Guzman, S.F., Borghi, E., Resende, Á.V. de, Silva, B.M., 2023. Assessment of soil water content variability using electrical resistivity imaging in an Oxisol under conservation cropping systems. Geoderma Regional 33. https://doi.org/10.1016/j.geodrs.2023.e00624

Silva, L.F. de O. da, Oliveira, A.F. de, Pio, R., Alves, T.C., Zambon, C.R., 2012. Quality variation of the olive oil in olive cultivars. Bragantia 202–209.

Soil Survey Staff, 2022. Keys to soil taxonomy, 13th ed.

Vanella, D., Ramírez-Cuesta, J.M., Longo-Minnolo, G., Longo, D., D'Emilio, A., Consoli, S., 2023. Identifying soil-plant interactions in a mixed-age orange

orchard using electrical resistivity imaging. Plant Soil 483, 181–197. https://doi.org/10.1007/s11104-022-05733-6

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses a guide to conservation planning. USDA, Agricultural handbook, 537.

Zhang, R., 1997. Infiltration models for the disk infiltrometer. Soil Science Society of America Journal 61, 1597–1603. https://doi.org/10.2136/sssaj1997.03615995006100060008x

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PAPER 3 - COVER CROP MANAGEMENT SYSTEMS IMPROVES SOIL QUALITY AND MITIGATE WATER EROSION IN TROPICAL OLIVE ORCHARDS

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Highlights

• Soil and water losses are negatively correlated to soil quality indices.

• Cover crop management systems improve soil quality and reduce water erosion.

• Spontaneous vegetation as cover crop showed better results in soil quality.

• Olive on bare soil can highlighting environmental degradation over the years.

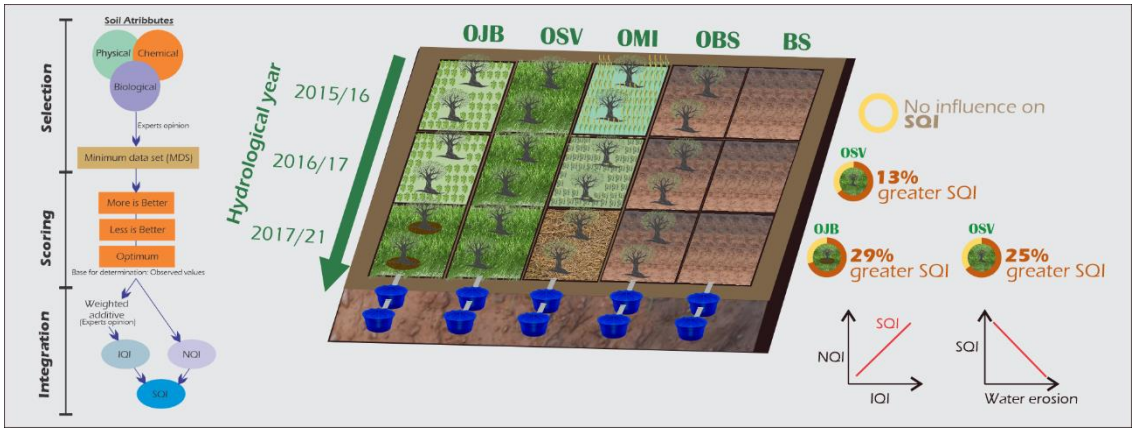
• Cover crop management requires care to conciliate with olive plantation growth.

Abstract

The production of olive trees in shallow soils in hillslopes requires adequate soil and water conservation systems. In this context, soil use and management besides vegetation cover contributes to better soil quality and the sustainability of the olive cultivation system. Thus, the objective was to determine the physical and chemical properties that are indicative of soil quality in areas of Dystrudepts, under different soil cover crop management systems in olive cultivation in tropical region. Olive tree culture field experiment was established in 2015, where soil was sampled over three years (2016, 2017 and 2021). The effect of five cover crop management systems were compared for each agricultural year, namely BS: bare soil in 2015/2016, 2016/2017 and 2017/2021; OBS: olive trees on bare soil in 2015/2016, 2016/2017 and 2017/2021; OSV: olive trees intercropped with mowed spontaneous vegetation in 2015/2016, 2016/2017 and 2017/2021; OJB: olive trees intercropped with jack beans (Canavalia ensiformis L.) in 2015/2016 and 2016/2017, and olive trees crowned intercropped with mowed spontaneous vegetation in 2017/2021; OMI: olive trees intercropped with millet (Pennisetum glaucum L.) in 2015/2016, olive trees intercropped with sunn hemp (Crotalaria juncea L.) in 2015/2017 and olive trees with spontaneous vegetations treated with herbicide (Roundup) in 2017/2021. The soil quality indices (SQI) proved to be sensitive to variations in different types of soil management from the second year of assessment, regarding water erosion. OSV and OJB showed the highest SQI, while OBS showed the lowest values. The SQI demonstrated an inverse correlation with soil and water losses starting from the second year of assessment. This highlights its efficacy in assessment the effects of adopted management on soil quality in the context of water erosion. Moreover, it reinforces the importance of vegetation cover in maintaining soil fertility, resulting in increase of soil organic matter and improving the structuring of Dystrudepts. The attributes that most correlated with the SQI were soil organic matter, effective cation exchange capacity, sum of bases, geometric mean diameter of aggregates, pH and unsaturated soil hydraulic conductivity. These attributes collectively provide valuable insights into soil health and water erosion susceptibility within the olive tree production system.

Keywords: Integrated quality index, Nemoro quality index, *Olea europaea* L., Soil health.

Graphical abstract



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1. Introduction

The olive (*Olea europaea* L.) is a temperate fruit plant of the *Oleaceae* family, native to the Mediterranean region, brought to Brazil by European immigrants during the country's colonization (Wrege et al., 2015). Despite being a tree, the olive has a small leaf area in its crown and, considering the adult phase, the plant's physiological need for large spacing between plants offers little protection to the soil (Guimarães et al., 2018; Beniaich et al., 2020; Guimarães et al., 2021; Beniaich et al., 2022; Beniaich et al., 2023) making the orchard environment susceptible to water erosion.

Olive orchards in Mediterranean region are often planted on sloping landscapes, with low soil fertility and low soil water storage. However, this practice has been proved unsustainable regarding soil erosion in the short- and long-term. OMI: olive trees intercropped with millet (*Pennisetum glaucum* L.) in 2015/2016, olive trees intercropped with sunn hemp (*Crotalaria juncea* L.) in 2015/2017 and olive trees with spontaneous vegetations treated with herbicide (Roundup) in 2017/2021 soil management practices based on intensive tillage or the application of chemical treatments to control spontaneous vegetation can reach soil losses above 20 Mg ha^{-1} $year^{-1}$ (Gómez et al., 2009; Vanwalleghem et al., 2011). Study with olive tree in Inceptisol in tropical region, in the absence of vegetation cover, can reach soil and water losses of approximately 308 to 292 Mg ha^{-1} $year^{-1}$ and 590 to 342 mm $year^{-1}$,

respectively, in the first two years of implantation of the olive orchard (Beniaich et al., 2020; Guimarães et al., 2021; Beniaich et al., 2023). The Inceptisol are shallow soils, with high silt content, block structure, low soil permeability to water, associated with high slopes and in the absence of protective vegetation cover, soil losses are unsustainable achieving 111 to 175 Mg ha^{-1} $year^{-1}$, and rapidly progressing to degradation due to water erosion (Santos et al., 1998; Schick et al., 2000; Silva et al., 2009).

In this way, soil and nutrient losses, mainly associated to water erosion are due to a combination of cultivation of olive trees in sloping areas and maintaining bare soils, through inadequate soil management. These factors represent significant challenge for both sustainability of production and the soil quality maintenance (Gómez et al., 2014; Guimarães et al., 2021). Soil erosion mitigation in olive cultivation is associated with the adoption of soil conservation practices. These strategies, including the adoption of cover crops management systems, aimed to protect the soil against the raindrop, reduce the splash erosion, minimize surface runoff, increase water infiltration and water storage in the soil, a, enhance sustainability and resilience in olive orchards in climate change context (Gómez et al., 2009; Keesstra et al., 2018; Beniaich et al., 2020; Arias-Giraldo et al., 2021; Beniaich et al., 2023).

Studies evaluating management systems involving spontaneous vegetation intercropped with olive trees, revealed that this practice served as a soil carbon reservoir and prevented nutrient and water losses by soil erosion (Guimarães et al., 2018; 2021). Cover crops have been recommended for improving soil chemical and physical properties, improving soil quality and sustainability (Arias-Giraldo et al., 2021; Santos et al., 2021; Beniaich et al., 2023).

Soil quality influences the balance and productivity of an ecosystem and its adjacent environments; however, defining and quantifying this aspect proved to be a challenging task, but in order to manage and maintain soils for future generations, their quality must be defined in order to cover the facets of the soil functions (Cândido et al., 2015). By definition, soil quality is the ability of the soil to function to sustain animal and plant productivity, maintain or improve water and air quality, as well as provide housing and human health (Karlen et al., 1997).

Among the various soil quality assessment methods, the soil quality indices (SQI) are the ones that best synthesize the attributes in a format that facilitates the understanding and the interpretation of processes and favors proper soil management

(Juhos et al., 2019). The SQI requires the identification of the minimum number of indicators that are preponderant based on previous research, that is, the minimum number of properties that represent soil quality. This will result in a minimal data set of soil indicators (Nabiollahi et al., 2017; Wu et al., 2019; Santos et al., 2021). Traditionally, physical and chemical soil attributes have been the main indicators used in assessing soil quality (Cândido et al., 2015; Muñoz-Rojas, 2018; Santos et al., 2021; Simon et al., 2022; Marion et al., 2022). Some studies have already selected physical and chemical attributes to be used as soil quality indicators (Cândido et al., 2015; Lima et al., 2016; Santos et al., 2021; Simon et al., 2022).

Indicators can be combined with additive indices, including the Integrated Quality Index (IQI), combining weight values of selected indicators in an index, by an equation with a simple scoring system (Santos et al., 2021), and the Nemoro Quality Index (NQI), based on the value of the indicator, without considering its weight (Guo et al., 2017). The IQI and NQI have already been shown to be sensitive to variations in susceptibility to water erosion under different soil management practices (Cândido et al., 2015; Santos et al., 2021).

Olive orchards in Brazil, specifically in the south of the state of Minas Gerais, are located in ecosystems sensitive to anthropic disturbances. The plantations have large spacing in rugged relief, high precipitation rates in soil with low natural fertility and weak physical structure, such as the case of the Inceptsol areas (Silva et al., 2009). Thus, the SQI assessment can constitute a tool to monitor the sustainability of the olive tree production system, as the SQI is effectively related to the soil properties due to the management practices adopted (Marion et al., 2022). Considering that soil and water losses can be significantly reduced by the effective management of cover crops, linking water erosion with the SQI, and the same based on a minimum data set of physical and chemical indicators, it can predict the impact of the olive orchards cropping system on soil susceptibility to erosion. In this way, estimating long-term sustainability and soil quality. Therefore, this research aims to identify the physical and chemical attributes that serve as indicators of soil quality concerning to soil and water losses, due to water erosion, in Dystrudepts area where soil cover crop management systems are employed in tropical olive tree cultivation.

2. Materials and Methods

2.1 Field experiment description

This research was conducted in the experimental farm of the Federal University of Lavras, Lavras, Minas Gerais, Brazil (21º13'20" S e 44º58'17" W), at an altitude 918 m a.s.l. (Fig. 1). According to Köppen Climate Classification System, the climate is classified as subtropical humid (Cwa), with the mean annual rainfall of 1,530 mm and the mean annual temperature of 19.4 ºC. The winter months are dry and cool, while the summer months are rainy with daily average temperature exceeding 22 ºC (Dantas et al., 2007).

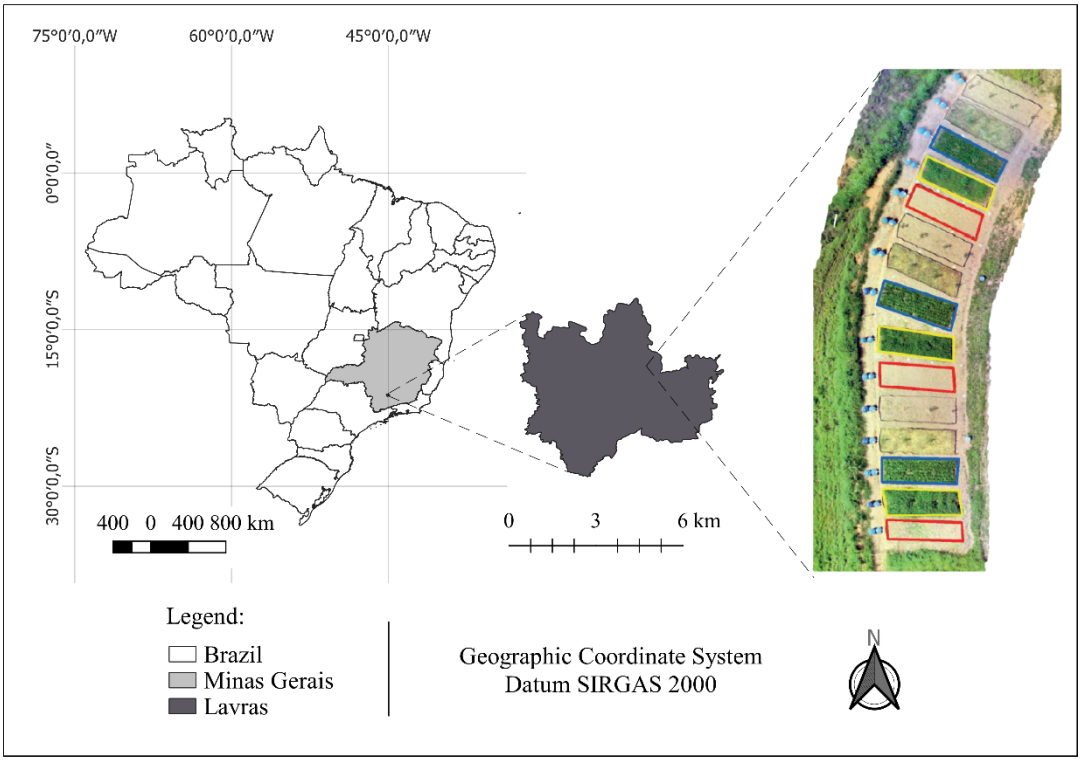

Fig. 1. Location of the experimental area (Lavras, Minas Gerais, Brazil) with arrangement of standard erosion plots to determine soil and water losses by water erosion.

The soil was classified as *Cambissolo Háplico Tb Distrófico* according to the Brazilian Soil Classification System (Santos et al., 2018), which corresponds to Dystrudepts in Soil Taxonomy (Soil Survey Staff, 2022), and to Dystric Cambisol in FAO Soil Classification System (IUSS Working Group WRB, 2022). The values of the physical and chemical attributes used as soil quality indicators are described in Table 1.

Table 1. Physical and chemical attributes of Dystrudepts soil under different cover management systems in olive growing in Lavras, Minas Gerais, Brazil. GMD: geometric mean diameter (aggregate stability); Ks: unsaturated soil hydraulic conductivity; TP: total porosity; MaP: macroporosity; MiP: microporosity; Bd: bulk density; SOM: soil organic matter; SB: sum of bases; t: effective cation exchange capacity, m: aluminum saturation percentage; BS: bare soil in 2016, 2017 and 2021; OBS: olive tree on bare soil in 2016, 2017 and 2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2016, 2017 and 2021; OJB: intercropped with jack beans (*Canavalia ensiformis* L.) in 2016 and 2017, and olive tree crowned intercropped with mowed spontaneous vegetation in 2021; OMI: olive trees intercropped with millet (*Pennisetum glaucum* L.) in 2016, olive trees intercropped with sunn hemp (*Crotalaria juncea* L.) in 2017, and olive trees with spontaneous vegetation treated with herbicide in 2021.

Attributes	**Treatments – 2016**				
	BS	**OBS**	**OSV**	**OJB**	**OMI**
GMD (mm)	4.20	3.64	3.82	4.20	4.10
Ks (mm h^{-1})	270.86	152.03	166.82	105.72	59.87
TP (cm^3 cm^{-3})	0.58	0.57	0.57	0.57	0.57
MaP (cm^3 cm^{-3})	0.30	0.29	0.29	0.28	0.29
MiP (cm^3 cm^{-3})	0.28	0.28	0.28	0.29	0.28
Bd (g cm^{-3})	1.48	1.48	1.51	1.49	1.55
SOM (g kg^{-1})	14.6	12.9	15.1	14.5	14.9
SB ($cmol_c$ dm^{-3})	2.76	2.35	2.46	2.29	2.71
t ($cmol_c$ dm^{-3})	2.81	2.52	2.59	2.51	2.86
m (%)	5.30	7.52	6.16	11.94	6.04
pH (H_2O)	5.27	5.19	5.64	5.16	5.43
Attributes	**Treatments – 2017**				
	BS	**OBS**	**OSV**	**OJB**	**OMI**
GMD (mm)	4.74	4.56	4.53	4.53	4.65
Ks (mm h^{-1})	98.40	79.29	167.77	280.26	190.93
TP (cm^3 cm^{-3})	0.68	0.70	0.71	0.68	0.69
MaP (cm^3 cm^{-3})	0.36	0.36	0.38	0.34	0.36
MiP (cm^3 cm^{-3})	0.32	0.34	0.33	0.32	0.33
Bd (g cm^{-3})	1.30	1.35	1.39	1.34	1.33
SOM (g kg^{-1})	18.8	15.4	17.4	18.3	19.3
SB ($cmol_c$ dm^{-3})	2.43	2.21	2.85	2.72	2.77
t ($cmol_c$ dm^{-3})	2.70	2.45	2.98	2.87	2.44
m (%)	11.56	10.97	7.23	9.91	8.01
pH (H_2O)	4.88	5.11	5.56	5.46	5.41
Attributes	**Treatments – 2021**				
	BS	**OBS**	**OSV**	**OJB**	**OMI**
GMD (mm)	4.31	4.24	4.52	4.84	4.71
Ks (mm h^{-1})	30.34	35.90	58.98	56.39	36.33
TP (cm^3 cm^{-3})	0.47	0.44	0.50	0.52	0.52
MaP (cm^3 cm^{-3})	0.18	0.18	0.16	0.18	0.18
MiP (cm^3 cm^{-3})	0.29	0.25	0.34	0.34	0.34
Bd (g cm^{-3})	1.20	1.26	1.20	1.26	1.35
SOM (g kg^{-1})	16.8	16.8	26.6	27.7	23.3
SB ($cmol_c$ dm^{-3})	2.21	2.91	3.97	4.21	3.12
t ($cmol_c$ dm^{-3})	2.52	3.03	4.06	4.30	3.24
m (%)	12.92	4.10	1.91	1.97	3.56
pH (H_2O)	4.98	5.03	5.63	5.57	5.18

Field experiment started in 2015, when the soil and water plots were installed and the olive tree was planted (Guimarães et al., 2018; Beniaich et al., 2020; Guimarães et al., 2021). During all years, the experimental area was divided into fifteen

experimental plots, consisting of five treatments with three replicates, distributed in the upper, middle and lower third of the area. The olive trees were transplanted in March 2015 following the slope direction. In each plot, a total of four olive trees were planted with spacing of 4 m in the line and 5 m between lines. The cultivar planted was Arberquina, the most cultivated in Brazil (Borges et al., 2017). In the olive plantation, we applied 100 g of limestone, 20 liters of manure, 500 g of single superphosphate, and 200 g of potassium chloride to each tree planting hole. For the annual fertilization in the 2015/2016 season, we applied 50 g of ammonium sulfate to each tree in November, December, and January. For the annual fertilization in the 2016/2017 season, we applied 100 g of ammonium sulfate, 50 g of potassium chloride, and 20 g of boric acid to each tree in October. Still in the 2016/2017 season, we applied 100 g of ammonium sulfate, 50 g of potassium chloride to each tree in December. In January, we applied 100 g of ammonium sulfate to each tree. During the dry season, we manually irrigated the olive plantation to meet the plants' water demands.

The experimental design consisted of five treatments (soil cover crop management systems) with three replicates in completely randomized blocks. The management of cover crop systems treatments, during all the research, are detailed in Table 2. The spontaneous vegetation was composed in 2016 and 2017 of grasses, being *Brachiaria decumbens* Stapf the dominant species, followed by *Digitaria sanguinalis* L., *Melinis minutiflora* P. Beauv., *Eleusine indica* L. and some broadleaf species such *Euphorbia heterophylla* L., *Amaranthus viridis* L., *Emilia fosbergii* Nicolson, *Ipomoea acuminata* Roem., *Conyza bonariensis* L., *Oxalis corniculata* L., and *Bidens pilosa* L. (Guimarães et al., 2021; Beniaich et al., 2020; Beniaich et al., 2023). In 2021, a new survey was carried out, with presented the following composition of plants, with the main dominant species found being *Brachiaria decumbens* Stapf and *Desmodium incanum* DC., and in a smaller proportion, *Amaranthus viridis* L., *Bidens pilosa* L., *Emilia fosbergii* Nicolson and some species of *Vernonia polyanthes* (Spreng.) Less. (Fig. 2).

Table 2. The management of cover crop treatment during the study in the olive tree orchard

Treatment	2015/16	2016/17	2017/21
OJB	olive trees intercropped with jack beans (*Canavalia ensiformis* L.)	olive trees intercropped with jack beans (*Canavalia ensiformis* L.)	olive trees crowned intercropped with mowed spontaneous vegetation
OSV	olive trees intercropped with mowed spontaneous vegetation	olive trees intercropped with mowed spontaneous vegetation	olive trees intercropped with mowed spontaneous vegetation
OMI	olive trees intercropped with millet (*Pennisetum glaucum* L.)	olive trees intercropped with sunn hemp (*Crotalaria juncea* L.)	olive trees intercropped with spontaneous vegetation treated with herbicide
OBS	olive trees on bare soil	olive trees on bare soil	olive trees on bare soil
BS	bare soil	bare soil	bare soil

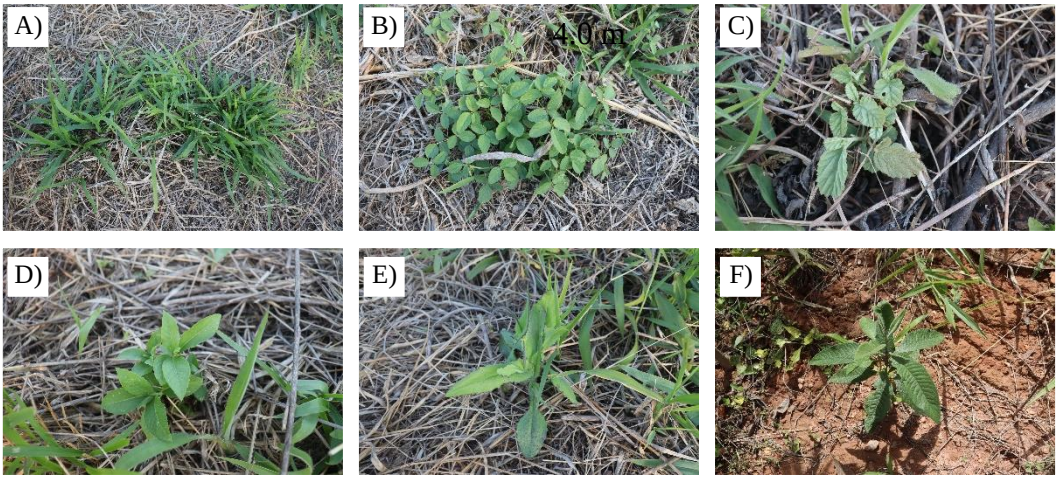

Fig. 2. Photographs showing the composition of the spontaneous vegetation in the experiment in 2021: A) *Brachiaria decumbens* Stapf, B) *Desmodium incanum* DC., C) *Amaranthus viridis* L., D) *Bidens pilosa* L., E) *Emilia fosbergii* Nicolson, F) *Vernonia polyanthes* (Spreng.) Less.

Cover crops (*Canavalia ensiformis* L - jack beans, *Pennisetum glaucum* L. - millet and *Crotalaria juncea* L. - sunn hemp) was manually seeded at the beginning of the rainy season of the booth hydrological years (November). In the jack bean treatment as a cover crop, the furrows were spaced at every 0.5 m in a density of eight seeds m^{-1}. In the millet and sunn hemp treatments, the spacing used was 0.25 m with densities of 90 and 40 seeds m^{-1}, respectively. Regarding the fertilization of the cover crops, 500 kg ha^{-1} of NPK (8:28:16), in the first crop season and 250 kg ha^{-1} of NPK (8:28:16), in the second crop season, were applied. For chemical weed control in BS, OBS and OMI plots, Roundup formulation was used as herbicide, according to the recommendation prescribed in the product leaflet (Monsanto, 2023).

2.2 Soil and water losses evaluation

Soil and water losses were evaluated following the methodology proposed by Wischmeier and Smith (1978), with changes in size, standard plots of size equal to 12 m in length and 4 m in width (Fig. 3). The mean slope of the plots was 0.23 m m^{-1}. Drainage and sediment collection were carried out according to Cogo et al. (2003) for each erosion event, using two 250 L tanks installed at the end of each plot. The first tank was connected to the second by a Geib-type divider, with nine inlet windows, so that when the first tank was completely full, 1/9 of the runoff volume would be conducted to the second tank.

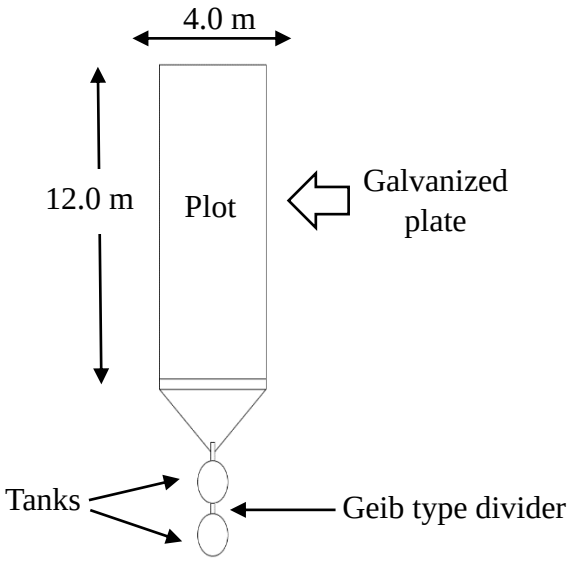

Fig. 3. Representative illustration of the standard plot of soil erosion.

The rainfall erosivity of each period was estimated based on the El_{30} index (Aquino et al., 2014; Nearing et al., 2017) (Eq. 1):

$$El_{30}=85.672*R_c^{0.6557} \quad (1)$$

The rainfall coefficient (R_c) was calculated using a model developed by Aquino et al. (2012) for the study region (Eq. 2):

$$R_c=\frac{p^2}{P} \quad (2)$$

Where R_c is the coefficient of rainfall (mm), p is the monthly precipitation (mm), and P of the annual precipitation (mm), the rainfall data were obtained from a weather station located at the Federal University of Lavras.

2.3 Crop performance

In 2016, 2017 and 2021, measurements of height, trunk diameter and crown radius (*R*) were carried out in the field in the 12 plots with olive trees, for later calculation of the *crown area* of the olive trees (Eq. 3):

$$Crown\ area = \pi * R^2 \quad (3)$$

2.4 Soil quality evaluation

Soil properties were evaluated in the three years, at the beginning of the June during the dry period of each year, in 2016, 2017 and 2021. We selected three points in each plot, at the top, in the middle and at the bottom, to sample soil depth of 0 – 0.20 m.

Undisturbed soil samples were collected using volumetric cylinders (0.079 m of height and 0.063 m of diameter). According Dane and Topp (2002) core methods, soil bulk density, total porosity, macro and microporosity (pores < 0,05 mm of diameter) were determined. Soil aggregates stability was performed in wet-sieve method and geometric mean diameter was calculated. Chemical soil properties were determined in soil fine fraction. All the methodologies related to quality indicators are mentioned in the Table 3.

Table 3. Physical and chemical indicators and their respective determination methodologies. GMD: geometric mean diameter; Ks: unsaturated soil hydraulic conductivity; TP: total porosity; MaP: macroporosity; MiP: microporosity; Bd: Bulk density; SOM: soil organic matter; SB: sum of bases; t: effective cation exchange capacity, m: aluminum saturation percentage.

Physical Attributes	**Method**	**Reference**
GMD (mm)	Yoder type sieves immersed in water	(Kemper and Rosenau, 1986; Silva et al., 2017)
Ks (mm h^{-1})	Minidisk Infiltrometer	(Zhang, 1997)
TP ($cm^3\ cm^{-3}$) MaP ($cm^3\ cm^{-3}$) MiP ($cm^3\ cm^{-3}$) Bd ($g\ cm^{-3}$)	Undisturbed soil samples (volumetric cylinder)	(Dane and Topp, 2002)
Chemical Attributes	**Method**	**Reference**
SOM ($g\ kg^{-1}$)	Oxidation with $Na_2Cr_2O_7 4N + H_2SO_4 10N$	(Walkley and Black, 1934)
SB ($cmol_c\ dm^{-3}$) t ($cmol_c\ dm^{-3}$) m (%)	Extractor: KCl 1 mol L^{-1} (Ca^{2+}, Mg^{2+}, Al^{3+}); Melich 1 (K^+). ($SB = Ca^{2+} + Mg^{2+} + K^+$); ($t = SB + Al^{3+}$); ($m = Al^{3+}\ t^{-1}$).	(Silva et al., 2017)
pH (H_2O)	H_2O in the ratio 1:2.5	(Silva et al., 2017)

To determine the physical and chemical soil quality indices, the attributes were considered according to their main functions in the soil (Table 4 and 5). Due to the differences in units between the indicators, standard scoring functions (SSF) were applied, which each indicator varying between 0 and 1. Based on soil quality, functions such as: “more is better”, “less is better” and “greater”, if the best soil functionality was associated with high, low or ideal values, respectively (Liebig et al., 2001) (Table 5).

The maximum and minimum values of each indicator were considered as upper and lower limits (Alvarenga et al., 2012; Rahmanipour et al., 2014). The values obtained were used in the SSF to normalize the results of each indicator in each soil sample.

To obtain the Integrated Quality Index (IQI), weights were assigned to the indicators according to their relevance for soil and water conservation (Table 4). The IQI was calculated for all treatments according to Eq. (4):

$$IQI = \sum_{i-1}^{n} Wi\ Ni \quad (4)$$

Where Wi is the weight of each indicator; and Ni, the indicator score.

The Nemoro Quality Index (NQI) was calculated for all treatments according to Eq. (5):

$$NQI = \sqrt{\frac{Pmean^2 + Pmin^2}{2} x\ \frac{n-1}{n}} \quad (5)$$

Where P*mean* is the mean of the selected indicator; P*min*, the minimum of the selected indicator scores in each sample of each treatment; and n is the number of indicators.

Table 4. Main functions and indicators of soil quality. Ks: unsaturated soil hydraulic conductivity; TP: total porosity; MaP: macroporosity; MiP: microporosity; Bd: bulk density; SOM: soil organic matter; GMD: geometric mean diameter (aggregate stability); t: effective cation exchange capacity; SB: sum of bases; m: aluminum saturation percentage.

Weight (IQI)	Soil functions	Physical Indicator	Chemical Indicator
0.25 or 25%	Receive, store and supply water	Ks	SOM
		MiP	-
		TP	-
		Bd	-
		GMD	-
0.25 or 25%	Promote root growth	MaP	SOM
		Bd	t
		-	SB
		-	m
		-	pH
0.25 or 25%	Store, supply and cycle nutrients	-	SOM
		-	t
		-	SB
		-	m
		-	pH
0.25 ou 25%	Promote soil conservation	Ks	SOM
		MaP	-
		Bd	-
		GMD	-
		-	-

Table 5. Standard scoring functions and indicator parameters in Dystrudepts at three depths under different soil cover management systems in the olive trees crop, in Lavras, Minas Gerais, Brazil. Indicators: Ind: indicator; FC: function type; GMD: geometric mean diameter (aggregate stability) (mm); Ks: unsaturated soil hydraulic conductivity (mm h^{-1}); TP: total porosity (cm^{-3} cm^{-3}); MaP: macroporosity (cm^{-3} cm^{-3}); MiP: microporosity (cm^{-3} cm^{-3}); Bd: bulk density (g cm^{-3}); SOM: soil organic matter (g kg^{-1}); SB: sum of bases ($cmol_c$ cm^{-3}); t: effective cation exchange capacity ($cmol_c$ cm^{-3}); m: aluminum saturation (%).

Ind	FT [1]	2016		2017		2021		Standard Scoring Function (SSF) [2]
		L	U	L	U	L	U	
GMD	MB	3.38	4.53	4.32	4.88	4.02	5.08	$MB: N(x) \begin{cases} 0.1 & x \le L \\ 0.9\frac{x-L}{U-L}+0.1 & L < x < U \\ 1 & x \ge U \end{cases}$
Ks	MB	23.42	316.6	34.11	324.5	26.07	81.12	
TP	MB	0.55	0.61	0.67	0.72	0.30	0.57	
MaP	MB	0.27	0.32	0.31	0.38	0.14	0.23	
MiP	MB	0.26	0.30	0.31	0.35	0.10	0.36	$LB: N(x) \begin{cases} 1 & x \le L \\ 1-0.9\frac{x-L}{U-L} & L < x < U \\ 0.1 & x \ge U \end{cases}$
Bd	LB	1.45	1.61	1.26	1.44	1.11	1.40	
SOM	MB	1.07	2.04	1.31	2.28	1.34	3.11	
SB	MB	1.59	3.48	2.01	3.23	1.56	4.45	$O: N(x) \begin{cases} 0.1 & x \le L1 \text{ ou } x \ge U2 \\ 0.9\frac{x-L1}{L2-L1}+0.1 & L1 < x < L2 \\ 1 & L2 \le x \le U1 \\ 0.9\frac{x-U1}{U1-U2}+0.1 & U1 < x < U2 \end{cases}$
t	MB	1.75	3.58	2.34	3.32	2.16	4.6	
m	LB	2.8	13.81	2.71	19.58	0	14.29	
pH	O	1: 3.5 2: 5.5	1: 6.5 2: 8.0	1: 3.5 2: 5.5	1: 6.5 2: 8.0	1: 3.5 2: 5.5	1: 6.5 2: 8.0	

[1] Function types: more is better (MB), less is better (LB) and optimum (O).
[2] Standard Scoring Functions (SSF), in these three equations x is the value of the indicator; N (x) is the score of the indicator ranging between 0.1 and 1; L and U are the lower and upper limits values, respectively.

2.5 Experimental and statistical design

Soil and water losses from the standard erosion plots were employed to relate erosion and soil quality indices.

To proceed with the analyses, after verifying the premises through linear models, which were subjected to normality, heteroscedasticity and variance test through graphical visualization (Kozak and Piepho, 2018) and numerical tests (Peña and Slate, 2006). When necessary, logarithmic transformations, square root, or general linear model methods were applied (Menke, 2015). It was necessary to perform the logarithmic method for the NQI, SQI and Water Loss in the 2016 assessment, perform the square root method for Soil Loss in the 2016 assessment, perform the general linear model for Crown radius and Cup area in the 2016 assessment, Soil and Water Losses in the 2017 assessment and Soil Loss in the 2021 assessment. Then, an analysis of variance (ANOVA) was performed between the indices within each treatment, considering the design in three randomized blocks, through the F test ($P < 0.05$). When ANOVA null hypothesis was rejected, comparisons were performed using the Tukey test ($P < 0.05$) to determine significant differences among means. Aiming to establish a

correlation between the soil attributes, the soil and water losses, and the quality indices, in each treatment, the principal component analysis (PCA) was carried out.

3. Results

The Fig. 4 shows precipitation values and rainfall erosivity from October to April during three hydrological years in 2015/2016, 2016/2017 and 2020/2021, the total rainfall erosivity was 5,291.69 MJ mm ha^{-1} h^{-1} $period^{-1}$, 3,723.30 MJ mm ha^{-1} h^{-1} $period^{-1}$ and 4,245.96 MJ mm ha^{-1} h^{-1} $period^{-1}$, respectively. Rainfall erosivity is concentrated in the months from November to March, with values close to or above 800 MJ mm ha^{-1} h^{-1} $period^{-1}$ in all periods evaluated, with the exception of February in the 2016/2017 period, with a peak of high erosivity rates varying between the months of November to January, reaching values of approximately 548 to 2,077 MJ mm ha^{-1} h^{-1} $period^{-1}$ in a single month.

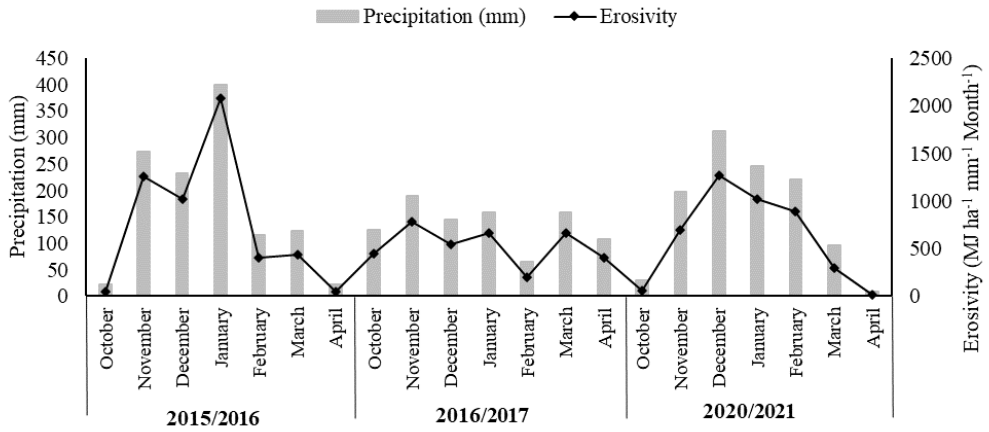

Fig. 4. Precipitation and rainfall erosivity for the study period

In relation to the two soil quality indicator methods (IQI and NQI) applied in the study, they were efficient in reproducing the variation in soil quality in the different soil cover management systems in the three years of evaluation. The linear relationship between the indices demonstrated a positive correlation, with R^2 = 0.83, 0.67, 0.97, and 0.90 in the years 2016, 2017, 2021 and the average of the all evaluated period times, respectively (Fig. 5). Therefore, it was decided to use the IQI and NQI (SQI) averages to check the correlation between the SQI and the soil and water losses represented in Fig. 6.

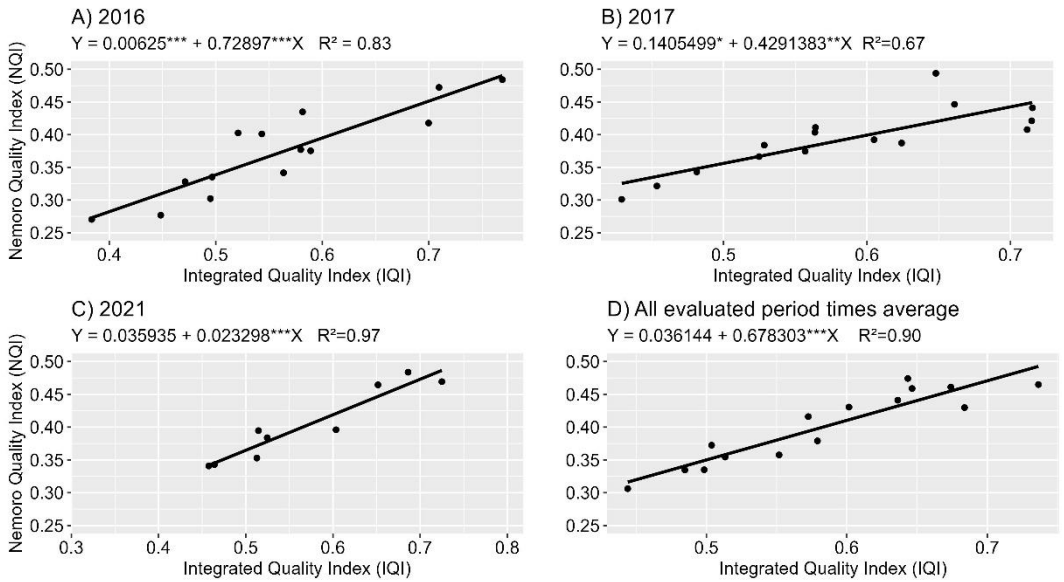

Fig. 5. Linear relationship between Nemoro (NQI) and Integrated (IQI) quality index for the years 2016, 2017, 2021 and all evaluated period times average.

The linear relationships between water erosion and the soil quality index only showed a significant effect ($P < 0.05$) for 2017 and the average of the all evaluated period times (Fig. 6C, 6D, 6G and 6H). Thus, soil and water losses negatively correlated to SQI, which demonstrate the relevance of the soil quality assessment study to define conservation practices in olive tree cultivation.

The indices of soil quality were significant ($P < 0.05$) in the assessments of land cover management systems in 2017 and 2021 (Table 6). From the second year of evaluation, the IQI and NQI was effective to report changes according to the management adopted. Analyzing the SQI (average of IQI and NQI), in 2027, the OSV treatment having a value of 0.55, being the highest value observed. In descending order, soil quality according to management was: OSV > OJB, OMI, BS > OBS. In 2021, the managements of OJB and OSV coverage showed bests soil quality, with a value of around 0.66 and 0.62, respectively. The indices distinguished three groups according to soil quality, in descending order, for SQI: OJB, OSV > OMI > OBS, BS.

In the first two years evaluated, the use of cover crops, in all treatments, reduced soil and water losses in relation to management that did not include vegetation cover (BS and OBS), in the order of 88.4 % for OSV, 70.7 % for OJB, and 78.2 % for OMI, in 2016, and 99.8 % for OSV, 99.9 % for OJB, and 97.1% for OMI, in 2017. There was also no difference, in all evaluations, between BS and OBS, confirming the high predisposition of olive tree cultivation to water erosion. In 2021, no difference was found between the cover management systems, as the soil and water loss factor varied

widely in this assessment, presenting coefficients of variation of 237.61 % and 60.27 %, respectively (Table 6).

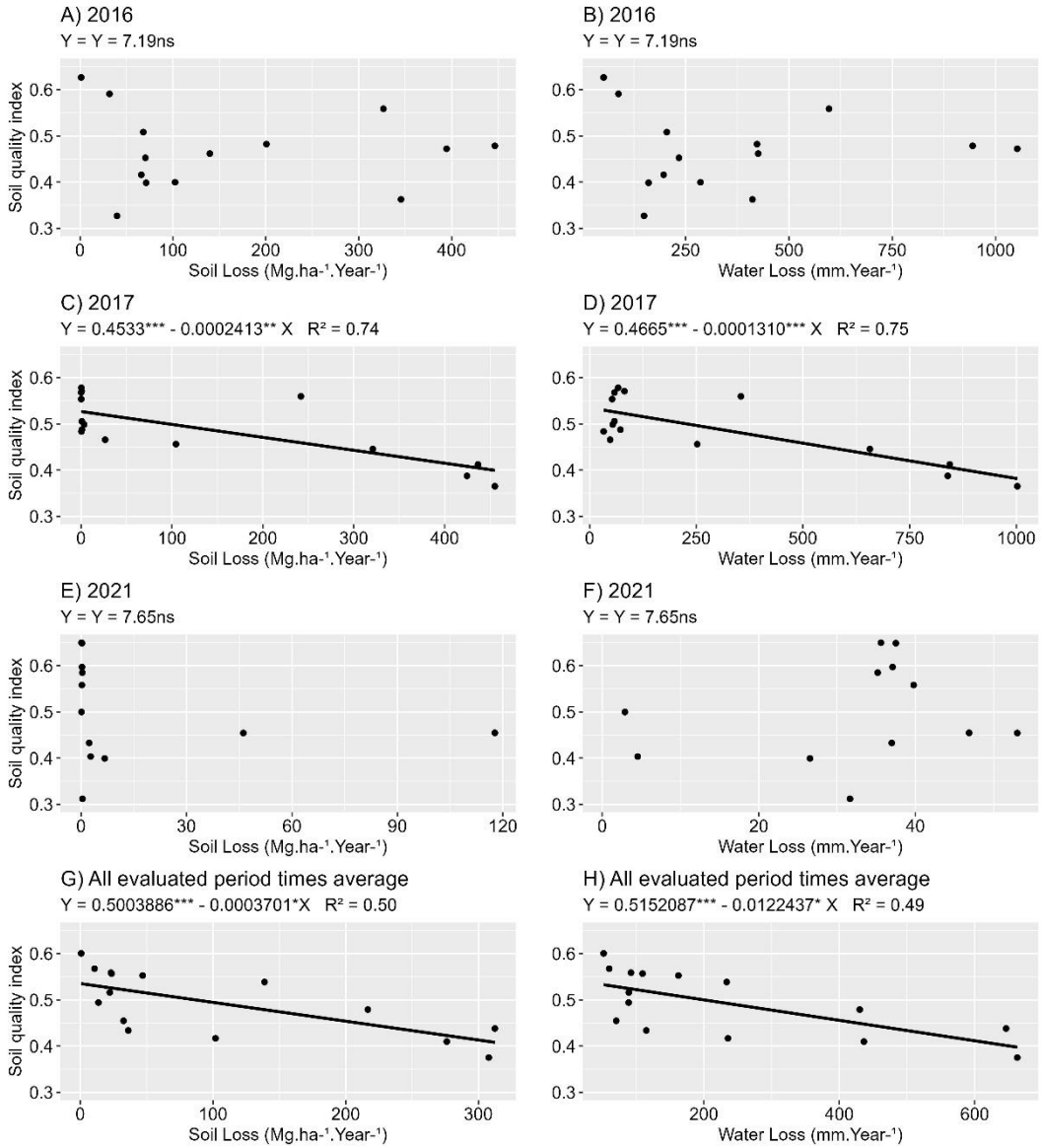

Fig. 6. Linear relationships between water erosion (soil and water losses) and the soil quality indices in the years 2016, 2017, 2021 and all evaluated period times average.

The results presented by the principal component analysis (PCA) (Fig. 7), among the treatments studied, the results of the IQI and NQI showed the positive influence of vegetation cover management on soil and water conservation, since the second year of cultivation (2016/2017) already showed a negative correlation with soil quality. In 2017 and 2021, the treatments that negatively correlated with the SQI were OBS and BS (Fig. 7B and 7C).

Table 6. Values of mean, standard deviation, and coefficient of variation (CV) of the Integrated quality index (IQI), nemoro quality index (NQI), mean soil quality indices (SQI_{mean}) and soil and water losses values in Dystrudepts, in three evaluation years (2016, 2017 e 2021) under different soil cover management systems in olive groves. BS: bare soil in 2016, 2017 and 2021; OBS: olive tree on bare soil in 2016, 2017 and 2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2016, 2017 and 2021; OJB: intercropped with jack beans (*Canavalia ensiformis* L.) in 2016 and 2017, and olive tree crowned intercropped with mowed spontaneous vegetation in 2021; OMI: olive trees intercropped with millet (*Pennisetum glaucum* L.) in 2016, olive trees intercropped with sunn hemp (*Crotalaria juncea* L.) in 2017, and olive trees with spontaneous vegetation treated with herbicide in 2021. Means followed by the same letter on the lines do not differ by Tukey test (P<0.05).

Year	Treatment	IQI	NQI	SQI_{mean}	Soil Loss (Mg ha^{-1} $period^{-1}$)	Water Loss (mm $period^{-1}$)
2016	BS	0.67±0.08 a	0.46±0.10 a	0.57±0.09 a	313.6±139.9 a	620.0±313.1 a
	OBS	0.53±0.07 a	0.35±0.07 a	0.44±0.07 a	313.6±100.9 a	629.0±366.8 a
	OSV	0.58±0.19 a	0.40±0.11 a	0.49±0.15 a	36.3±33.6 c	135.0±77.4 c
	OJB	0.53±0.03 a	0.36±0.04 a	0.44±0.02 a	92.0±41.4 b	286.0±122.8 b
	OMI	0.56±0.13 a	0.39±0.09 a	0.46±0.11 a	68.3±35.4 bc	178.0±100.3 bc
	CV (%)	19.73	21.55	19.92	87.92	79.67
2017	BS	0.56±0.14 ab	0.36±0.05 b	0.46±0.10 ab	339.4±107.9 a	671.2±324.1 a
	OBS	0.49±0.04 b	0.35±0.03 b	0.42±0.03 b	321.9±188.5 a	645.2±340.4 a
	OSV	0.64±0.08 a	0.45±0.04 a	0.55±0.05 a	0.65±0.3 b	73.6±7.5 b
	OJB	0.63±0.08 ab	0.40±0.02 ab	0.52±0.04 ab	0.46±0.4 b	49.8±14.7 b
	OMI	0.61±0.05 ab	0.40±0.04 ab	0.51±0.04 ab	9.99±14.4 b	51.7±3.2 b
	CV (%)	15.97	12.54	13.98	137.71	118.17
2021	BS	0.43±0.10 b	0.31±0.06 c	0.37±0.08 b	10.2±10.1 a	35.20±7.9 a
	OBS	0.47±0.08 b	0.34±0.08 bc	0.41±0.08 b	54.8±59.1 a	43.90±11.0 a
	OSV	0.73±0.05 a	0.51±0.06 ab	0.62±0.05 a	0.2±0.2 a	24.20±20.8 a
	OJB	0.77±0.03 a	0.56±0.03 a	0.66±0.02 a	0.1±0.1 a	25.50±19.2 a
	OMI	0.57±0.10 ab	0.40±0.06 abc	0.49±0.08 ab	1.0±1.5 a	15.70±20.8 a
	CV (%)	25.90	26.13	25.86	237.61	60.27

By cluster analysis using PCA (Fig. 7), it was found that the BS treatment differed from all other treatments in all years evaluated, and the OBS treatment differed from the others in the evaluation period corresponding to 2021, the OMI treatment as an exception. When analyzing the all evaluated period times average, the treatments that contained cover crop management did not differ from each other, but they did differentiate from BS (Fig. 7D).

Throughout the three years of evaluation, several variables exhibited a positive correlation with the soil quality index (SQI) (Fig. 7). These variables included soil organic matter, effective cation exchange capacity and sum of bases. Starting from the second year of evaluation, additional indicators as soil pH and unsaturated soil hydraulic conductivity became positively correlated to SQI. Conversely, aluminum saturation percentage was negatively correlated in the three years evaluated, and soil

and water losses from the second years onwards (2017) were negatively correlated with the SQI.

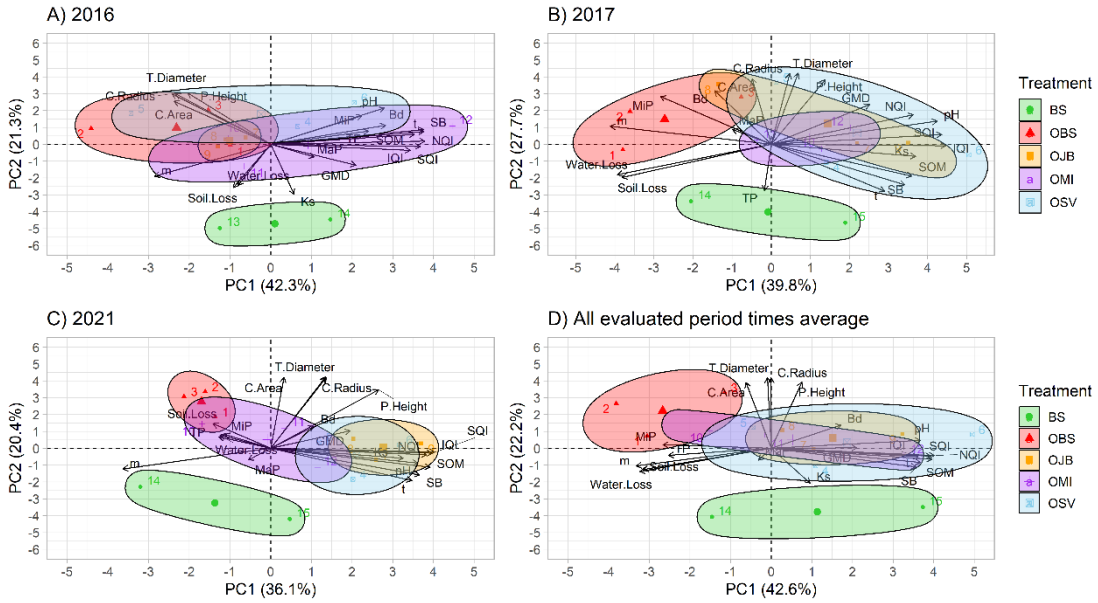

Fig. 7. Principal component analysis for soil physical and chemical attributes in the years 2016 (A), 2017 (B), 2021 (C) and all evaluated period times average (D). OJB: olive trees (*Olea europaea* L.) intercropped with jack beans (*Canavalia ensiformis* L.) in 2016 and 2017, and olive trees crowned intercropped with mowed spontaneous vegetation in 2021; OMI: olive trees intercropped with millet (*Pennisetum glaucum* L.) in 2016, olive trees intercropped with sunn hemp (*Crotalaria juncea* L.) in 2017, and olive trees with spontaneous vegetation treated with herbicide in 2021; OSV: olive trees intercropped with mowed spontaneous vegetation in 2016, 2017 and 2021; OBS: olive trees on bare in 2016, 2017 and 2021; BS: bare soil in 2016, 2017 and 2021. SB: sum of bases; t: effective cation exchange capacity; m: aluminum saturation percentage; MOS: soil organic matter; Bd: bulk density; MaP: macroporosity; MiP: microporosity; TP: total porosity; GMD: geometric mean diameter; Ks: unsaturated soil hydraulic conductivity; SQI: soil quality index; NQI: nemoro quality index; IQI: integrated quality index; P. Height: plant height; C. Radius: crown radius; T. Diameter: trunk diameter; PC1: principal component 1; PC2: principal component 2.

The olive plants growth data are presented in Table 7. In the first two years of plant evaluation (2016 and 2017), the treatment of olive trees intercropped with millet and later replaced by sunn hemp cover (OMI) presented the lowest growth response, respectively in 2016 and 2017, 70.1 cm and 169.6 cm in plant height, 22.5 cm and 54.4 cm in crown radius, 1.17 cm and 2.84 cm in trunk diameter and 0.16 cm and 0.93 cm of crown area. The highest plant growth values occurred for olive trees grown on bare soil (OBS) in 2016 and 2017. However, in 2021, there was no difference between cover crop management for olive tree growth variables.

Table 7. Values of mean, standard deviation, and coefficient of variation (CV) of the olive plantation performance for each period and in different soil cover management systems in olive cultivation. BS: bare soil in 2016, 2017 and 2021; OBS: olive tree on bare soil in 2016, 2017 and 2021; OSV: olive tree intercropped with mowed spontaneous vegetation in 2016, 2017 and 2021; OJB: intercropped with jack beans (*Canavalia ensiformis* L.) in 2016 and 2017, and olive tree crowned intercropped with mowed spontaneous vegetation in 2021; OMI: olive trees intercropped with millet (*Pennisetum glaucum* L.) in 2016, olive trees intercropped with sunn hemp (*Crotalaria juncea* L.) in 2017, and olive trees with spontaneous vegetation treated with herbicide in 2021. Means followed by the same letter on the lines do not differ by Tukey test ($P<0.05$).

Year	Treatment	Plant height	Crown radius	Trunk diameter	Cup area
		----------cm----------			m²
2016	OBS	173.0±10.2 a	62.9±6.9 a	2.99±0.5 a	1.25±0.3 a
	OSV	137.8±39.7 a	50.2±6.8 ab	2.38±0.4 ab	0.80±0.2 b
	OJB	125.9±10.7 a	39.7±3.1 b	2.02±0.1 b	0.50±0.1 bc
	OMI	70.1±16.9 b	22.5±2.4 c	1.17±0.3 c	0.16±0.03 c
	CV (%)	34.13	36.74	34.85	65.74
2017	OBS	257.7±18.8 a	94.8±15.4 a	4.54±0.7a	2.88±0.9 a
	OSV	217.6±43.5 ab	70.8±12.2 ab	3.64±0.6 ab	1.61±0.5 ab
	OJB	240.3±11.5 ab	70.1±7.2 ab	3.73±0.3 ab	1.55±0.3 ab
	OMI	169.6±38.6 b	54.4±4.8 b	2.84±0.7 b	0.93±0.2 b
	CV (%)	19.68	24.34	21.84	50.09
2021	OBS	280.7±29.3 a	262.0±47.2 a	28.3±6.8 a	22.03±7.4 a
	OSV	259.5±45.5 a	164.0±59.0 a	16.2±5.5 a	9.18±6.2 a
	OJB	288.6±17.5 a	183.0±12.0 a	21.0±3.5 a	10.54±1.4 a
	OMI	233.5±2.6 a	189.0±51.4 a	18.9±4.2 a	11.74±5.7 a
	CV (%)	12.41	27.75	30.45	53.54

4. Discussion

Due to the rainfall erosivity, the study region has a high risk of water erosion, particularly between the months of November to March (Silva et al., 2009), with special attention between the months of November to January, which may be aggravated by inadequate management practices, as previously reported by several studies (Aquino et al., 2014; Lima et al., 2018; Beniaich et al., 2020; Beniaich et al., 2022; Beniaich et al., 2023). The total rainfall erosivity values, for the same period and region, reported in this study are in line with those observed by Beniaich et al. (2023), varying between 3,448 and 5,249 MJ mm ha^{-1} h^{-1} $period^{-1}$.

Concerning soil quality indices employed, IQI and NQI, the high correlation observed between them (Fig. 5) is important to state the recommendation of the NQI for soil quality assessments. This choice eliminates researcher bias associated with the assignment of weights to soil quality indicators (Cândido et al., 2015). Few studies in Brazil focus on the assessment of soil quality, including a more comprehensive assessment of soil chemical and physical indicators in an integrated manner. Due to the

complexity of the concepts, there is no universal methodology for assessing soil quality, despite this, the well-conducted assessments generally follow a three-step approach: selection, interpretation and integration of indicators into a single index (Rinot et al., 2019; Simon et al., 2022), among them the IQI and NQI (Cândido et al., 2015; Guo et al., 2017; Santos et al., 2021). Cândido et al. (2015), assessing the effectiveness of these two indices, and reported no significant difference between them, such as the results found in this study.

Soil and water losses negatively correlated with soil quality in 2017 and in the average values of the three years evaluated, confirmed by the linear coefficient obtained between them (Fig. 6C, 6D, 6G and 6H) and by principal component analysis (Fig. 7B and 7D). These results highlight the importance of studying soil quality assessment to employ the most appropriate conservation management practices (Cândido et al., 2015). Hence, previously knowledge about best practices that improve soil quality may aid conservationist olive orchard management.

The OSV treatment showed better results in relation to soil quality in 2017 with 0.64 and 0.45, in IQI and NQI, respectively. After six years of cover crop management (2021), in addition to OSV, OJB management also showed better results in relation to soil quality with 0.73 and 0.77 for IQI and 0.51 and 0.56 for IQN, respectively. In relation to OSV, the OSB management reduced 26.6 % and 33.9 % of SQI in 2017 and 2021, respectively, highlighting environmental degradation over the years if adequate coverage management systems are not adopted.

The OSV consisting mainly of Poaceas (*B. decumbens*) as cover crops since the first survey of spontaneous vegetation plants, in 2016 (Beniaich et al., 2020; Guimarães et al., 2021, Beniaich et al., 2023), as shown in Fig. 2A. Spontaneous vegetation plants can induce significant changes in soil indicators associated with soil quality, increasing diversity of soil bacterial communities, improving soil structure and therefore reducing erosion processes (Arias-Giraldo et al., 2021), furthermore, spontaneous vegetation was the most efficient in quickly reducing soil and water losses in the first year (Table 6) as they have a great capacity for growth in the first rains when compared to the other cover crops presented in our study. In the following years, OSV did not differ in relation to other cover crops used, confirming its importance in the sustainability of the olive orchards.

The OJB, in the first two hydrological years, by employing the use of legumes (jack beans – *C. ensiformis* L.), increased the SQI by 22% over the years (Table 6), this

was due to the diversification that occurred in this coverage management, therefore, according to Serri et al. (2022), sequences with high agricultural diversification can increase chemical parameters such as organic carbon and total organic nitrogen, along with physical parameters such as basic infiltration rate. Furthermore, jack beans are characterized by a long-term cycle in the region under study, which allowed the soil to be protected for a prolonged period in OJB management (Beniaich et al., 2023).

The elevate values of soil and water losses, in the absence of coverage, can be explained by the high rainfall erosivity registered in this research (Fig. 4). The rainfall pattern in the area is characterized as the advanced pattern that leads elevated soil loss per event, being influenced by the low soil permeability of the Inceptsol (Aquino et al., 2013). Furthermore, the high erodibility of Inceptisols in southeastern Brazil, the previous soil moisture, absence of soil cover and surface sealing caused by the impact of raindrops contribute to the increase in water erosion (Silva et al., 2009; Beniaich et al., 2023). As for water losses in cultivated soils, the values are critical for agricultural crops, especially in shallow and sloping soils, and can be aggravated in periods of greater water deficit, due to the loss of nutrients and organic matter that go with the water loss (Beniaich et al., 2020).

Due to the elevated coefficients of variation observed in the study area in 2021 for both soil and water losses, it was not possible to detect differences during this evaluated period, among the soil cover management systems of water erosion (Table 6). The elevated soil losses observed in 2016 and 2017 in plots with cover crops (jack beans, millet and sunn hemp) are due to soil preparation and planting practices (Beniaich et al., 2020), in addition to the limited capacity of the chosen cover plants to reduce water erosion rates (Lima et al., 2018; Santos et al., 2021).

When analyzing the indicators that composes the soil quality index, the use of cover crops is a conservation practice that can improve soil quality, reducing compaction, increasing porosity, improving soil aggregate stability and enhancing carbon and nitrogen content in the soil, and among the indicators that tend to be most responsive, in all soil textures, are soil hydraulic parameters and soil organic matter (Hao et al., 2022).

The pH reflects the availability of nutrients in general, while exchangeable acidity (aluminum saturation) reflects the opposite, due to the presence of exchangeable Al in the cation exchange site of the soil. Thus, the study showed that soil quality has an influence on maintaining soil fertility and soil and water losses on their decrease over

time, as demonstrated in the principal components analysis (Fig. 7). Studies with olive trees in the Mediterranean on soils with slopes varying between 4 and 11 % showed rapid responses to conventional soil preparation management and the use of ryegrass (*Lolium multiflorum*) as a cover crop, where water retention curves in the soil detected changes in terms of soil degradation in conventional cultivation, and improvements in the increase in soil organic matter content in the line between trees in cover management (Guzmán et al., 2019).

The Ks is an indicator that hydraulic parameters that depend on the soil quality structural, which favor the reduction of erosion. Thus, the study demonstrated that for Dystrudepts in sloping areas, susceptible to erosion, in addition to the chemical variables of soil fertility (SOM and pH) the hydraulic parameters (Ks) is a determining variable in the assessment if soil sensitivity to water erosion reflecting on soil quality, as observed by Serri et al. (2022). In the research it was possible to verify that the Ks correlated positively with the SQI studied and negatively with soil and water losses since the second year evaluated (Fig. 7B and 7C), indicating this improvement in soil quality and water erosion control.

In the first year, there was no discernible impact on soil quality due to soil cover management. However, it is worth noting that previous research has highlighted multiple benefits of adopting cover crops in olive orchards in sloped areas. The benefits encompass increased soil organic carbon sequestration, improved soil structure, elevation of soil organic matter, nitrogen and macronutrient content, reduced compaction and controlled water erosion, but these benefits manifest in the long-term (Arias-Giraldo et al., 2021; Guimarães et al., 2021). Among the ideal chemical attributes to increase soil quality and promote favorable conditions for olive cultivation, a positive correlation with productivity were soil organic matter content –between 1 and 3 %–, and the pH level –between 6 and 7– (Doğan and Gülser, 2020). In our study, only the soil organic matter contents were ideal (Table 1).

Soils with vegetation cover tend to exhibit well-structure soil, increasing microporosity, which is directly related to aeration, compaction and soil water dynamics, due to the proliferation of roots facilitated by direct planting or vegetation spontaneous as a cover crop (Zuazo et al., 2020). A similar result was reported by Parlak et al. (2015) studying the use of legumes and grasses as cover crops in the assessment of soil erosion using a rainfall simulator. In such research, the authors highlighted that just

two years were not enough to increase soil organic matter content and the soil aggregates stability in olive orchards.

The results of the study demonstrated a negative effect of cover crops on the initial development of olive trees, mainly with the use of crops that have a greater capacity for competition, such as millet in 2015/2016 (Table 7). In the second year of evaluation, it was possible to highlight that the olive tree grown in bare soil had better performance in terms of height, crown radius, trunk diameter and crown area (Table 7), as a result, it was decided to continue the research by choosing the cover crop that would least affect the development of the olive tree, the spontaneous vegetation. From 2017, the cover crops managements OSV and OJB showed statistically similar olive tree growth performance than OBS.

The use of soil cover can benefit farmers to achieve resilient cropping systems and partially alleviate the long-term challenges caused by climate change (less vulnerability to water erosion from extreme precipitation events in susceptible soils). Furthermore, at a local scale, improving soil quality advances towards sustaining high-yield cropping systems and brings greater clarity about the possible interactions among soil, plants, human activity and ecosystem services (Keesstra et al., 2018; Santos et al., 2021). All these results emphasize the need to promote the use of cover crops to improve long-term soil conservation and the sustainability of olive cultivation (Arias-Giraldo et al., 2021) in Brazilian orchards, especially in the tropical region and in areas at risk of severe erosion processes.

5. Conclusions

1. The assessment of two soil quality indices, IQI and NQI, demonstrated sensitivity to variations in different types of soil management from the second year onwards, in the context of water erosion. It became evident that one year of research was insufficient to show differences between soil quality indices. However, in terms of soil and water losses, from the second year of evaluation onwards, an inverse gradient was reveled regarding to soil quality, therefore, allowing to estimate long-term sustainability and soil quality. Thus, the tested indices made it possible to effectively assess the impacts of the adopted management practices in olive orchard on soil quality in relation to water erosion.
2. The physical-chemical indicators that positively correlated with soil quality in the three years evaluated were soil organic matter, effective cation exchange capacity

and the sum of bases. From the second year, in addition to those mentioned, the pH and unsaturated soil hydraulic conductivity also exhibited a positive correlation with soil quality. The indicator that correlated in relation to soil and water losses in the six years evaluated was aluminum saturation.

3. Introducing cover crops in the first years of olive orchard requires a tailored management approach that balances competition and ensuring the unimpeded growth of the olive tree. Cover cultivation with spontaneous vegetation and mowing management with or without crowning the olive tree not only allows the development of the plant, but also improves soil conditions, reduces water erosion and progressive increase soil quality indices over time.

CRediT authorship contribution statement

Eduardo Medeiros de Oliveira: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Gabriele Medeiros Hermógenes:** Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Larissa da Costa Brito:** Investigation, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Bruno Montoani Silva:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Junior Cesar Avanzi:** Funding acquisition, Supervision, Validation, Visualization, Writing – review & editing. **Adnane Beniaich:** Supervision, Validation, Visualization, Writing – review & editing. **Marx Leandro Naves Silva:** Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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7. References

Alvarenga, C.C., de Mello, C.R., de Mello, J.M., da Silva, A.M., Curi, N., 2012. Soil quality index associated to the groundwater techarge (SQI GR) in the upper Rio Grande basin, Minas Gerais. Rev. Bras. Cienc. Solo 36, 1608–1619. https://doi.org/10.1590/S0100-06832012000500025

Aquino, R.F., Silva, M.L.N., Freitas, D.A.F. de, Curi, N., Avanzi, J.C., 2013. Soil losses from typic cambisols and red latosol as related to three erosive rainfall patterns. Rev. Bras. Ciênc. Solo 37(1), 213–220. https://doi.org/https://doi.org/10.1590/S0100-06832013000100022

Aquino, R.F., Silva, M.L.N., Freitas, D.A.F. de, Curi, N., Mello, C.R. de, Avanzi, J.C., 2012. Spatial variability of the rainfall erosivity in southern region of Minas Gerais state, Brazil. Cienc. e Agrotec. 36, 533–542. https://doi.org/https://doi.org/10.1590/S1413-70542012000500006

Aquino, R.F., Silva, M.L.N., Freitas, D.A.F. de, Curi, N., Mello, C.R. de, Avanzi, J.C., 2014. Rainfall erosivity and recurrence time for Lavras, Minas Gerais, Brazil. Rev. Ceres 61 (1), 09–16. https://doi.org/https://doi.org/10.1590/S0034-737X2014000100002

Arias-Giraldo, L.F., Guzmán, G., Montes-Borrego, M., Gramaje, D., Gómez, J.A., Landa, B.B., 2021. Going beyond soil conservation with the use of cover crops in mediterranean sloping olive orchards. Agronomy 11. https://doi.org/10.3390/agronomy11071387

Beniaich, A., Guimarães, D.V., Avanzi, J.C., Silva, B.M., Acuña-Guzman, S.F., dos Santos, W.P., Silva, M.L.N., 2023. Spontaneous vegetation as an alternative to cover crops in olive orchards reduces water erosion and improves soil physical

properties under tropical conditions. Agric. Water Manag. 279, 108186. https://doi.org/10.1016/j.agwat.2023.10818

Beniaich, A., Silva, M.L.N., Guimarães, D.V., Bispo, D.F.A., Avanzi, J.C., Curi, N., Pio, R., Dondeyne, S., 2020. Assessment of soil erosion in olive orchards (*Olea europaea* L.) under cover crops management systems in the tropical region of Brazil. Rev. Bras. Cienc. Solo 44. https://doi.org/10.36783/18069657rbcs20190088

Beniaich, A., Silva, M.L.N., Guimarães, D. V., Avalos, F.A.P., Terra, F.S., Menezes, M.D., Avanzi, J.C., Cândido, B.M., 2022. UAV-based vegetation monitoring for assessing the impact of soil loss in olive orchards in Brazil. Geoderma Reg. 30. https://doi.org/10.1016/j.geodrs.2022.e00543

Borges, T.H., López, L.C., Pereira, J.A., Cabrera-Vique, C., Seiquer, I., 2017. Comparative analysis of minor bioactive constituents (CoQ10, tocopherols and phenolic compounds) in Arbequina extra virgin olive oils from Brazil and Spain. J. of Food Composition and Analysis 63, 47–54. https://doi.org/10.1016/J.JFCA.2017.07.036

Cândido, B.M., Silva, M.L.N., Curi, N., De Freitas, D.A.F., Mincato, R.L., Ferreira, M.M., 2015. Indicator indexing methods in assessment of soil quality in relation to water erosion. Rev. Bras. Cienc. Solo 39, 589–597. https://doi.org/10.1590/01000683rbcs20140363

Cogo, N.P., Levien, R., Schwarz, R.A., 2003. Soil and water losses by rainfall erosion influenced by tillage methods, slope-steepness classes, and soil fertility levels. Rev. Bras. Cienc. Solo 27, 743–753. https://doi.org/10.1590/S0100-06832003000400019

Dane, J.H., Topp, G.C., Methods of soil analysis: Physical methods. Madison, Soil Science Society of America, 2002. Part 4. 1692p.

Dantas, A.A.A., Carvalho, L.G. de, Ferreira, E., 2007. Climatic classification and tendencies in Lavras region, MG. Cienc. e Agrotec. 31, 1862–1866. https://doi.org/10.1590/S1413-70542007000600039

Doğan, B., Gülser, C., 2020. Soil quality assessment for olive groves areas of menderes district, Izmir-Turkey. Eurasian J. of Soil Sci. 9, 298–305. https://doi.org/10.18393/ejss.758380

Gómez, J.A., Guzmán, M.G., Giráldez, J.V., Fereres, E. 2009. The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. Soil Tillage Res. 106, 107-144. https://doi.org/10.1016/j.still.2009.04.008

Gómez, J.A., Infante-Amate, J., Molina, M.G., Vanwalleghem, T., Taguas, E.V., Lorite, I. 2014. Olive cultivation its impact on soil erosion and its progression into yield impacts in southern Spain in the past as a key to a future of increasing climate uncertainty. Agric. 4, 170-198. https://doi.org/10.3390/agriculture4020170

Guimarães, D.V., Silva, M.L.N., Beiniach, A., Bispo, D.F.A., Contins, J.G.P., Curi, N., 2018. Relationship between soil organic matter fractions and cover plants in olive post planting. Rev. Bras. Frutic. 40, 1–12. https://doi.org/10.1590/0100-29452018027

Guimarães, D.V., Silva, M.L.N., Beniaich, A., Pio, R., Gonzaga, M.I.S., Avanzi, J.C., Bispo, D.F.A., Curi, N., 2021. Dynamics and losses of soil organic matter and nutrients by water erosion in cover crop management systems in olive groves, in tropical regions. Soil Tillage Res. 209. https://doi.org/10.1016/j.still.2020.104863

Guo, L., Sun, Z., Ouyang, Z., Han, D., Li, F., 2017. A comparison of soil quality evaluation methods for Fluvisol along the lower Yellow River. Catena 152, 135–143. https://doi.org/10.1016/j.catena.2017.01.015

Guzmán, G., Perea-Moreno, A.J., Gómez, J.A., Cabrerizo-Morales, M.Á., Martínez, G., Giráldez, J.V., 2019. Water related properties to assess soil quality in two olive orchards of south Spain under different management strategies. Water 11. https://doi.org/10.3390/w11020367

Hao, X., Abou Najm, M., Steenwerth, K.L., Nocco, M.A., Basset, C., Daccache, A., 2022. Are there universal soil responses to cover cropping? A systematic review. Sci. of the Total Environ. https://doi.org/10.1016/j.scitotenv.2022.160600

IUSS Working Group WRB, 2022. World reference base for soil resources: international soil classification system for naming soils and creating legends for soil maps, 4th ed. Viena.

Juhos, K., Czigány, S., Madarász, B., Ladányi, M., 2019. Interpretation of soil quality indicators for land suitability assessment – A multivariate approach for Central European arable soils. Ecol. Indic. 99, 261–272. https://doi.org/10.1016/j.ecolind.2018.11.063

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., Soil Science Society of America, 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61.

Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A., 2018. The superior effect of nature based solutions in land management for enhancing ecosystem services. Sci. of the Total Environ. https://doi.org/10.1016/j.scitotenv.2017.08.077

Kemper, W.D., Rosenau, R.C., 1986. Aggregate Stability and Size Distribution, in: Klute, A. (Ed.), Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods, 5.1, Second Edition. pp. 425–442. https://doi.org/https://doi.org/10.2136/sssabookser5.1.2ed.c17

Kozak, M., Piepho, H.P., 2018. What's normal anyway? Residual plots are more telling than significance tests when checking ANOVA assumptions. J. Agron. Crop Sci. 204, 86-98. https://doi.org/https://doi.org/10.1111/jac.12220

Liebig, M.A., Varvel, G.E., Doran, J.W., 2001. A simple performance-based index for assessing multiple agroecosystem functions. Agron. J. 93, 313–318. https://doi.org/10.2134/agronj2001.932313x

Lima, G.C., Silva, M.L.N., Freitas, D.A.F. de, Cândido, B.M., Curi, N., Oliveira, M.S. de, 2016. Spatialization of soil quality index in the sub-basin of Posses, Extrema, Minas Gerais. Rev. Bras. Eng. Agrícola e Ambient. 20, 78–84. https://doi.org/10.1590/1807-1929/agriambi.v20n1p78-84

Lima, P.L.T., Silva, M.L.N., Quinton, J.N., Batista, P.V.G., Cândido, B.M., Curi, N., 2018. Relationship among crop systems, soil cover, and water erosion on a typic

Hapludox. Rev. Bras. Cienc. Solo 42. https://doi.org/10.1590/18069657rbcs20170081

Marion, L.F., Schneider, R., Cherubin, M.R., Colares, G.S., Wiesel, P.G., da Costa, A.B., Lobo, E.A., 2022. Development of a soil quality index to evaluate agricultural cropping systems in southern Brazil. Soil Tillage Res. 218. https://doi.org/10.1016/j.still.2021.105293

Menke, W. 2015. Review of the generalized least squares method. Surv. Geophys 36, 1-25. https://doi.org/10.1007/s10712-014-9303-1

Monsanto do Brasil LTDA, 2023. Bula Roundup Original Mais, 01119 ed.

Muñoz-Rojas, M., 2018. Soil quality indicators: critical tools in ecosystem restoration. Curr. Opin. Environ. Sci. Health. 5, 47–52. https://doi.org/10.1016/j.coesh.2018.04.007

Nabiollahi, K., Taghizadeh-Mehrjardi, R., Kerry, R., Moradian, S., 2017. Assessment of soil quality indices for salt-affected agricultural land in Kurdistan Province, Iran. Ecol. Indic. 83, 482–494. https://doi.org/10.1016/j.ecolind.2017.08.001

Nearing, M.A., Yin, S., Borrelli, P., Polyakov, V.O., 2017. Rainfall erosivity: An historical review. Catena 157, 357–362. https://doi.org/10.1016/j.catena.2017.06.004

Parlak, M., Özaslan Parlak, A., Türkmen, E., 2015. The effect of cover crops to soil erosion in olive orchards. Ege Üniversitesi Ziraat Fakültesi Dergisi 52, 49–56.

Peña, E.A., Slate, E.H. 2006. Global validation of linear model assumptions. J. Am. Stat. Assoc. 10, 341-354. https://doi.org/10.1198/016214505000000637

Rahmanipour, F., Marzaioli, R., Bahrami, H.A., Fereidouni, Z., Bandarabadi, S.R., 2014. Assessment of soil quality indices in agricultural lands of Qazvin Province, Iran. Ecol. Indic. 40, 19–26. https://doi.org/10.1016/j.ecolind.2013.12.003

Rinot, O., Levy, G.J., Steinberger, Y., Svoray, T., Eshel, G., 2019. Soil health assessment: A critical review of current methodologies and a proposed new approach. Sci. of the Total Environ. 648, 1484–1491. https://doi.org/10.1016/j.scitotenv.2018.08.259

Santos, D., Curi, N., Ferreira, M.M., Evangelista, A.R., Cruz Filho, A.B., Teixeira, W.G. 1998. Soil losses and productivity of improved native pastures under different management practices. Pesq. Agropec. Bras. 33(2), 183-189.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C. dos, Oliveira, V.Á. de, Lumbreras, J.F., Coelho, M.R., Almeida, J.A. de, Araújo Filho, J.C. de, Oliveira, J.B. de, Cunha, T.J.F., 2018. Sistema brasileiro de classificação de solos, 5ª. ed. Empresa Brasileira de Pesquisa Agropecuária, Brasília, DF.

Santos, W.P. dos, Silva, M.L.N., Avanzi, J.C., Acuña-Guzman, S.F., Cândido, B.M., Cirillo, M.Â., Curi, N., 2021. Soil quality assessment using erosion-sensitive indices and fuzzy membership under different cropping systems on a Ferralsol in Brazil. Geoderma Reg. 25. https://doi.org/10.1016/j.geodrs.2021.e00385

Serri, D.L., Pérez-Brandan, C., Meriles, J.M., Salvagiotto, F., Bacigaluppo, S., Malmantile, A., Vargas-Gil, S., 2022. Development of a soil quality index for sequences with different levels of land occupation using soil chemical, physical and microbiological properties. Applied Soil Ecol. 180, 104621. https://doi.org/10.1016/j.apsoil.2022.104621

Schick, J., Bertol, I., Batistela, O., Balbinot Júnior, A.A., 2000. Water erosion in clayey inceptisol in different crop and tillage systems: I. Soil and water losses. Rev. Bras. Cienc. Solo 24, 427–436. https://doi.org/10.1590/S0100-06832000000200019

Silva, A.M. da, Silva, M.L.N., Curi, N., Avanzi, J.C., Ferreira, M.M., 2009. Rainfall erosivity and erodibility of Cambisol (Inceptisol) and Latosol (Oxisol) in the region of Lavras, Southern Minas Gerais State, Brazil. Rev. Bras. Cienc. Solo 33, 1811–1820. https://doi.org/10.1590/S0100-06832009000600029

Silva, A.E. da, Fontana, A., Melo, A. da S., Martins, A.L. da S., Inda, A.V., Santi, A., Madari, B.E., Mattos, B.B., Almeida, B.G. de, Alves, B.J.R., Jantalia, C.P., Pérez, D.V., Campos, D.V.B. de, Villani, E.M. de A., Martins, E. de S., Oliveira, E.M. de, Clemente, E. de P., Novotny, E.H., Bona, F.D. de, Balieiro, F. de C., Andrade, F.V., Gregoris, G., Donagemma, G.K., Valladares, G.S., Debiasi, H., Ruiz, H.A., Assis, I.R. de, Fink, J.R., João Herbert Moreira, Viana, J.H.M., Araújo Filho, J.C. de, Correa, J.C. de O., Salton, J.C., Franchini, J.C., Pires, L. de O.B., Anjos, L.H.C. dos, Hernani, L.C., Saldanha, M.F.C., Corrêa, M.M., Sá, M.A.C. de,

Fontes, M.P.F., Coelho, M.R., Tomazi, M., Cooper, M., Dias Junior, M. de S., Torres, M.G., Martins, P.C.C., Soares, P.F.C., Teixeira, P.C., Freitas, P.L. de, Machado, P.L.O. de A., Fernandes, R.B.A., Cantarutti, R.B., Ralisch, R., Novais, R.F., Calderano, S.B., Castro, S.S. de, Bianchi, S.R., Bhering, S.B., Pérez, S.P.V., Dechen, S.C.F., Venegas, V.H.A., Klein, V.A., Benites, V. de M., Escaleira, V., Teixeira, W.G., Silva, W.M., 2017. Manual de métodos de análise de solo, 3rd ed. Empresa Brasileira de Pesquisa Agropecuária - Embrapa Solos, Rio de Janeiro.

Simon, C. da P., Gomes, T.F., Pessoa, T.N., Soltangheisi, A., Bieluczyk, W., de Camargo, P.B., Martinelli, L.A., Cherubin, M.R., 2022. Soil quality literature in Brazil: A systematic review. Rev. Bras. Cienc. Solo 46. https://doi.org/10.36783/18069657rbcs20210103

Soil Survey Staff, 2022. Keys to soil taxonomy, 13th ed.

Vanwalleghem, T., Amate, J.I., Molina, M.G., Fernández, D.S., Gómez, J.A. 2011. Quantifying the effect of historical soil management on soil erosion rates in Mediterranean olive orchards. Agric., Ecosyst. Environ. 142, 341-351. https://doi.org/10.1016/j.agee.2011.06.003

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

Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses, a guide to conservation planning. USDA, Agric. handbook, 537.

Wrege, M.S., Coutinho, E.F., Pantano, A.P., Jorge, R.O., 2015. Potential distribution of olive in Brazil and worldwide. Rev. Bras. Frutic. 37, 656–666. https://doi.org/10.1590/0100-2945-174/14

Wu, C., Liu, G., Huang, C., Liu, Q., 2019. Soil quality assessment in Yellow River Delta: Establishing a minimum data set and fuzzy logic model. Geoderma 334, 82–89. https://doi.org/10.1016/j.geoderma.2018.07.045

Zhang, R., 1997. Infiltration models for the disk infiltrometer. Soil Science Society of America Journal 61, 1597–1603. https://doi.org/10.2136/sssaj1997.03615995006100060008x

Zuazo, V.H.D., Rodríguez, B.C., García-Tejero, I.F., Ruiz, B.G., Tavira, S.C., 2020. Benefits of organic olive rainfed systems to control soil erosion and runoff and improve soil health restoration. Agron. Sustain. Dev. 40. https://doi.org/10.1007/s13593-020-00644-