



Effect of cover crop management system on olive orchards: Soil morphological and micromorphological alterations

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ABSTRACT

Olive production in Brazil 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 Dystrudepts under different cover crop management systems through field observations and micromorphological analyses. An eight-year study was conducted to assess the effects 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, enhanced soil structure, total porosity, A horizon thickness, and therefore minimized soil loss over six years. The presence of illuvial clay film fragments highlights the role of erosive forces in detaching and redistributing fine soil particles 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.

1. Introduction

The olive tree (*Olea europaea* L.) is a temperate fruit species native to the Mediterranean region and has been cultivated in Brazil for over a century (Wrege et al., 2015; Aparecido et al., 2023). Brazil offers suitable areas for olive cultivation, primarily in the south and southeast regions, with the state of Minas Gerais standing out due to its favorable 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 (Zuazo et al., 2020; Guimarães et al., 2021; Márquez-García et al., 2024). These include cultivation on bare soil, frequent episodes of erosive rainfall, low canopy cover along ridges, and the physiological requirement for wide spacing between trees (Guimarães et al., 2018). 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 slopes, high silt content, dense structure, and low water permeability (Silva et al., 2009; Skorupa et al., 2017; Benevenuto et al., 2025). In this context, cover crops management has been recommended to enhance soil structure as well as its chemical and physical properties (Santos et al., 2021; Silva et al., 2021; Oliveira et al., 2024).

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; 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; Brito et al., 2025), and prevent nutrient losses through erosion (Guimarães et al., 2021). However, there is no single optimal soil cover approach for a specific crop, as plant-soil interactions are essential for improving soil health and ecosystem services.

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Soil physical properties play a crucial role in crop production, particularly those related to soil structure, which are key indicators of soil quality and agricultural performance (Silva et al., 2015; Serafim et al., 2019; Oliveira et al., 2024). Soil structure and aggregation are dynamic attributes that directly influence water infiltration and, consequently, crop development (Cruz et al., 2024; Jimenez et al., 2025). These attributes are shaped by a complex natural and anthropogenic process that modify the soil pore architecture at both micro-aggregates and macroaggregates scales (Reis et al., 2025). In this context, soil organic matter is fundamental factor regulating structural stability and aggregation processes (Kapur et al., 2007).

The visual assessment of soil structure can be conducted through the morphological description of soil profiles in the field, analyzing each horizon or layer individually based on traditional pedological characterization (Anjos et al., 2025). Additionally, micromorphological analyses of undisturbed samples 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 and integrative approach than conventional methods for visualizing soil microstructure, enabling the elucidation of soil processes, underlying mechanisms, pedogenetic pathways, and the behavior and functioning of the soil system (Canisares et al., 2020; Anjos et al., 2025).

Although advances in soil physical assessment have improved the understanding of soil responses to land use and management, most studies still rely on soil physical indicators or macrometer-scale observations, which provide limited insights into the internal organization, aggregation patterns, plasmic fabric relationships, and overall structural coherence (Reis et al., 2025). These structural attributes are controlled by microscale processes that cannot be adequately captured by conventional measurements, highlighting the need for micromorphological approaches capable of linking form and function within the soil matrix (Canisares et al., 2020). Furthermore, meaningful interpretation of soil structural dynamics requires relatively long-term agronomic observations (Kapur et al., 2007), however, studies integrating micromorphology with long-term field experiments remain scarce. This lack is particularly evident in tropical Inceptisols under perennial cropping systems, where management-induced changes in soil structure may

occur gradually and heterogeneously, emphasizing the necessity of integrated field and micromorphological investigations to elucidate the mechanisms underlying soil structural improvement or degradation.

In this context, this research aimed to evaluate soil structure and microstructure through morphological descriptions of Dystrudepts subjected to different cover crop management systems, combining systematic field observations with thin-section analyses. We hypothesized that distinct cover crop management systems would differentially modify soil structural and microstructural attributes by enhancing biopore formation, promoting greater aggregate stability, and increasing the expression of microscale features, interconnected pore networks, and more cohesive microaggregate assemblages. This integrated field–micromorphological approach was expected to elucidate soil structural processes that remain undetectable using conventional soil physical measurements.

2. Material and methods

2.1. Field experiment description

This research was conducted in erosion plots located within the experimental area of the Federal University of Lavras, Minas Gerais, Brazil (21°13'20" S and 44°58'17" W), at an altitude of 918 m a.s.l. (Fig. 1). The climate is classified as a subtropical highland climate (Cwb) according to the Köppen Climate Classification System (Alvares et al., 2014), with a mean annual rainfall of 1383.4 mm and a mean annual temperature of 20.6 °C (INMET, 2022). Winters are dry and cool, whereas summers are characterized by higher rainfall and daily average temperatures exceeding 22 °C (Dantas et al., 2007). The soil is classified as a *Cambissolo Háplico Tb Distrófico* according to the Brazilian Soil Classification System (Santos et al., 2025), corresponding to Dystrudepts 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 the contiguous plot. The cultivar planted was Arbequina, the most cultivated in Brazil

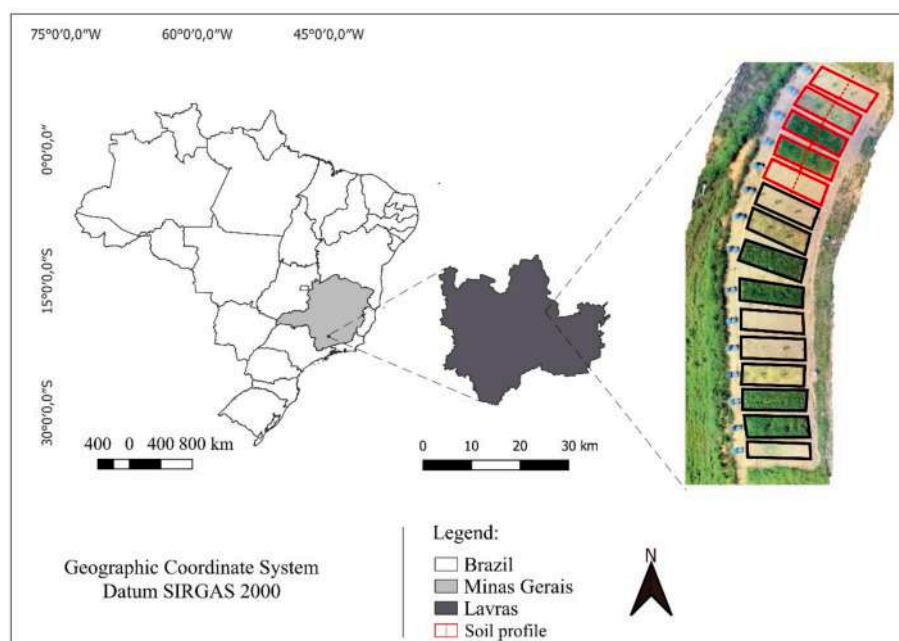


Fig. 1. Location of the experimental area (Lavras, Minas Gerais, Brazil). UAV image (2016).

(Borges et al., 2017). Each tree planting hole (40 cm deep and 40 cm wide) received 100 g of limestone, 20 L 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 per month 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. Additionally, we applied 100 g of ammonium sulfate, and 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 water demands of plants.

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 (monoculture); 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 vegetation; 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 and 2023, the experiment remained fallow with the olive trees, according to the treatments.

The sequence of cover crop species within each treatment was defined based on functional group strategies and adaptive management criteria. During the initial years, treatments were designed to represent contrasting functional groups, including legume-based systems (jack bean), grass-legume succession (millet followed by sunn hemp), and spontaneous vegetation. These strategies aimed to promote distinct mechanisms of soil structural modification, such as organic matter inputs with different C:N ratios, root system architecture, and biopore formation.

From the third year onward, spontaneous vegetation management was adopted in selected treatments based on preliminary field observations and erosion monitoring, which indicated superior soil protection and structural performance. This standardization allowed the assessment of the persistence and legacy effects of the initial cover crop strategies under a more uniform and operationally realistic management condition.

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 as *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, showing 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^{-2} . In the millet and sunn hemp treatments, the spacing used was 25 cm with densities of 90 and 40 seeds m^{-2} , 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 applied.

2.2. 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 determined 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 was determined using wet-sieving method (Yoder procedure) and geometric mean diameter (GMD) was 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^{-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.

The organic carbon content (TOC) 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 soil organic matter content (SOM) was estimated from the TOC using a conversion factor of 0.58:

$$SOM = \frac{TOC}{0.58} \quad (1)$$

Based on the data on sampling depth, SOM, and bulk density, the carbon stock (CS) was calculated using: where CS was the soil carbon stock, z was the thickness of the soil layer, Bd was the bulk density and TOC was the total organic carbon content. The pH was determined using H_2O in the ratio 1:2.5. Exchangeable K and available P were determined using the Melich 1 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 in Silva et al. (2017).

In 2023, one soil profile was opened in the center of one plot (block) per treatment at depth of 0–60 cm, and samples were collected for morphological description (Anjos et al., 2025). This plot was selected as representative based on the overall similarity of soil physical and chemical attributes among blocks (Fig. 1). 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.

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.

These samples were initially air dried and subsequently subjected to a controlled drying process, including oven drying at 40 °C for seven days, followed by 60 °C for three days, and finally 100 °C for 24 h. 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 °C for 4 h, and cured at 140 °C for 4 h. The resulting resin blocks 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, they were trimmed and polished to an ideal thickness of 30 µm to carry out the micromorphological description of the thin sections (Stoops, 2003).

2.3. Statistical analysis

Morphological and micromorphological observations were based on a single representative block per treatment and were used exclusively for qualitative interpretation, whereas statistical analyses were performed using data from all three blocks.

The normality, heteroscedasticity, and variance test premises of the soil physical and chemical properties, 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 or square root transformations were applied, or outliers were removed to meet model assumptions.

After verification of all assumptions, data were subjected to analysis of variance (ANOVA), considering cover crop management systems as

the only fixed factor and three randomized blocks. Statistical analyses were conducted separately for each evaluation year (2016 and 2021) and for each soil layer (0–20 cm and 20–40 cm). Therefore, year and soil depth were not included as factors in the statistical model, and no interactions involving these variables were tested. When the ANOVA F-test indicated significant differences among treatments ($P < 0.05$), mean comparisons were performed using the test of Tukey ($P < 0.05$).

3. Results

3.1. Soil physical properties and water erosion

The results of bulk density, porosity (macro-, micro-, and total porosity), aggregate size and stability, and 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 compared to the OBS treatment in 2016, and compared to both the OBS and BS treatments in 2021. In general, the soil physical properties of macro- and microporosity were not affected by the treatments across soil layers and years. However, for total porosity, there was an increase in pore distribution in the OJB treatment at 20–40 cm depth in 2016, but not in 2021, suggesting an improvement in soil structuring in the first year of the study. In both layers and years, the cover crop management systems had no effect on aggregate stability.

The soil loss results showed that the BS and OBS treatments had the

Table 2
Soil physical and chemical properties of the Dystrudepts 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	1.48	1.49	1.51	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	0.29	0.30	0.28	0.29	0.29	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	0.12	0.15	0.14	0.20
Microporosity (cm ³ cm ⁻³)	0–20	ns	0.26	0.28	0.29	0.28	0.29	ns	0.22	0.25	0.26	0.25	0.26
	20–40	ns	0.28	0.28	0.29	0.29	0.29	ns	0.24	0.22	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	0.38	0.34	0.40	0.38	0.42
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
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
Chemical													
Soil organic matter (g kg ⁻¹)	0–20	ns	16.7	12.8	14.4	14.1	17.1	*	24.3 ab	16.9 b	27.9 a	26.7 ab	23.4 ab
	20–40	ns	8.14	7.61	7.02	8.92	8.41	ns	7.45	7.59	6.01	11.88	9.20
Carbon Stock (t C ha ⁻¹)	0–20	ns	0.26	0.22	0.25	0.24	0.30	*	0.23 b	0.25 b	0.40 a	0.37 ab	0.36 ab
	20–40	ns	0.14	0.14	0.13	0.15	0.15	ns	0.09	0.12	0.10	0.16	0.11
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 soil (cmol _c dm ⁻³)	0–20	ns	2.58	2.49	2.48	2.98	2.83	ns	3.23	3.02	4.28	4.04	3.51
	20–40	ns	2.06	1.89	1.59	1.80	1.84	*	2.35	2.42	1.90	2.50	1.99

Values are treatment means. For each evaluation year and soil layer, means followed by different letters within the same row differ statistically according to the test of Tukey ($P < 0.05$); when no significant differences were detected, “ns” is indicated. Year and soil depth were not considered as factor in the statistical analysis. 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.

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.

3.2. Soil chemical properties

In 2016, none of the evaluated soil chemical properties were affected by the cover crop management systems, indicating the absence of short-term effects (Table 2). In contrast, after six years of cultivation, significant changes were observed in 2021, particularly in the 0–20 cm soil layer.

Overall, plots managed with cover crops showed higher soil organic matter content, carbon stock, sum of bases, and available phosphorus when compared with bare soil and olive monoculture treatments, highlighting the general positive effect of soil cover on surface soil fertility.

When individual cover crops systems were compared, distinct responses were observed. The OJB system resulted in the highest soil organic matter content, carbon stock, and sum of bases, indicating a broader improvement in soil chemical quality. The OSV treatment showed similarly high values for the sum of bases, although with intermediate organic matter contents. In contrast, the OMI system promoted a significant increase in available phosphorus, reflecting a more specific effect on nutrient availability.

In the 20–40 cm layer, soil chemical properties were not significantly affected by the cover crop management systems in 2021, suggesting that the observed effects were mainly restricted to the surface layer.

3.3. 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 morphology

(Fig. 2).

In the BS treatment, four horizons were identified: A (0–9 cm), B (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 3, Fig. 2A). 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 differences in the degree of weathering of 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), BA horizon (7–24 cm), and B horizons (B1: 24–40 cm, B2: 40–60+ cm). The structure was consistently stronger than in BS, with larger, angular blocks in the A and AB horizons. The B horizon had a hard consistency, with a color progression from 10R 4/6 (moist) to 10R 5/8 (dry) (Table 3, Fig. 2B), indicating deeper soil weathering without significant exposure of the parent material.

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 3, Fig. 2C). 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 3, Fig. 2D). 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 (12–26 cm), and a B horizon (26–60+ cm) (Table 3, Fig. 2E). 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

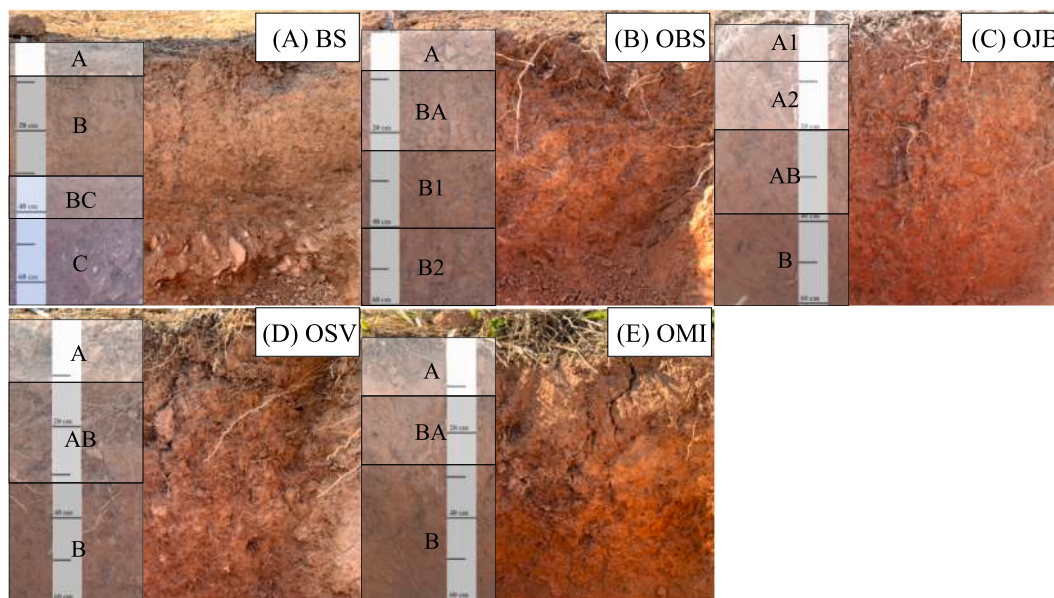


Fig. 2. Soil profiles: (A) BS - bare soil in 2015–2021 and fallow land in 2021–2023; (B) OBS - olive tree on bare soil in 2015–2021 and fallow land in 2021–2023; (C) OJB - olive tree intercropped with jack beans in 2015–2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017–2021, 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.

Table 3
Morphological description of the different cover crop managements.

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

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; OBJ: 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.

potential soil aggregation (Table 3, Fig. 2E).

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 color. The BS, OBS, and OBJ treatments exhibited continuous vertical pores, in contrast to the OSV and OMI treatments, which displayed high porosity but lacked visible connectivity. Additionally, the OBJ treatment showed a noticeable presence of angular gneiss gravel. Finally, the OSV treatment exhibited a reddish coloration in the upper part 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 speckled. The pedofeatures were 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 granostratified. The pedofeatures were Fe nodules in dissolution (Table 4, Fig. 5).

In contrast, the OBJ treatment displayed more developed micromorphological features, with the presence of Fe nodules and a matrix pedofeature strongly impregnated. The microstructure remained angular with weak separation, but the poro- and granostratified micromass indicated improved organic content compared to BS and OBS. There was a presence of planar and vughs voids. This intercropping system promoted more advanced soil formation processes (Table 4, Fig. 6). The OSV treatment showed a similar microstructure, with moderately separated angular blocks, and planar, vughs, and chambers voids. However, the micromass was speckled and crystallitic, and the pedofeatures included remnants of clay coating (Table 4, Fig. 7).

Lastly, the OMI treatment demonstrated micromorphological features similar to OBJ, with iron nodules. The micromass was poro- and granostratified, and root fragments were observed, reflecting a higher degree of organic matter incorporation and enhanced soil development under this treatment. There was a presence of planar, vughs, and chamber voids (Table 4, Fig. 8).

4. Discussion

4.1. Soil physical properties and water erosion

The cover crop management systems affected soil physical properties and erosion dynamics, particularly during the first hydrological year (2015/2016). Overall, management effects were more pronounced for soil and water losses, bulk density at depth, and total porosity in the initial years, whereas macroporosity, microporosity, and aggregate stability were not affected by cover crop management systems in either evaluation year (Table 2).

Bulk density responses varied according to soil depth and management system. In the surface layer (0–20 cm), no significant differences among treatments were observed in either year, indicating that bulk density in this layer is strongly controlled by recurrent surface processes, such as water erosion, rainfall impact, surface sealing, and particle redistribution, which tend to homogenize structural conditions across cover crop management systems. In contrast, in the 20–40 cm layer, the OMI treatment consistently exhibited lower bulk density compared with

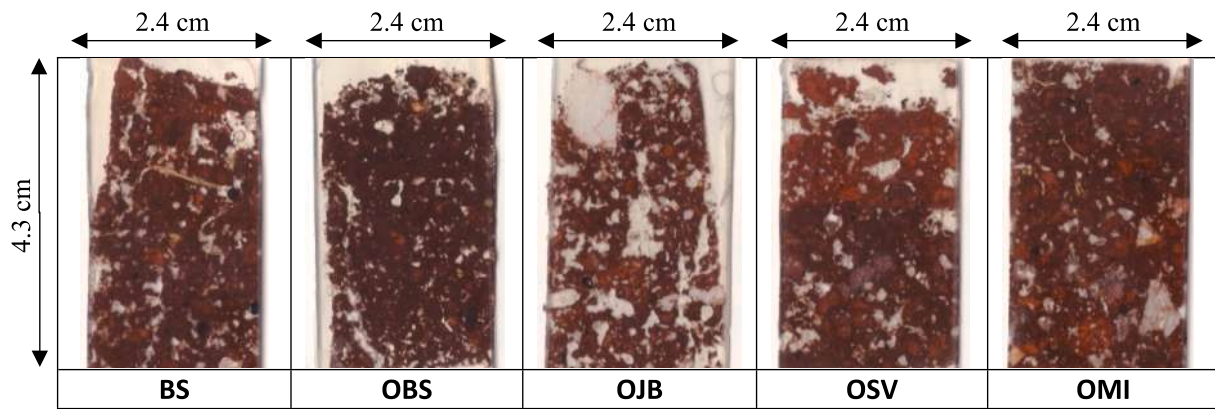


Fig. 3. Scanned images of thin sections of soil (depth of 0–4.3 cm and width of 2.4 cm, with a thickness of 0.01 cm). BS: bare soil in 2015–2021 and fallow land in 2021–2023; OBS: olive tree on bare soil in 2015–2021 and fallow land in 2021–2023; OJB: olive tree intercropped with jack beans in 2015–2017, 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.

Table 4
Micromorphological description of the different cover crop managements.

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

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.

OBS in 2016 and with both OBS and BS in 2021. This response suggests that root activity, biopore formation, and biological structuring associated with cover crops were effective in modifying subsurface soil structure (Melo et al., 2023; Silva et al., 2021), where disturbance by surface erosion process and rainfall impacting is less intense, even under shallow tropical Incetisols.

Macroporosity and microporosity did not differ significantly among treatments across soil layers and years, indicating that changes promoted by cover crop management were either spatially heterogeneous or occurred at scales not fully captured by bulk porosity measurements. This result suggests that structural modifications occurred primarily through localized rearrangement and biological structuring processes, which may not be captured by integrative porosity measurements, as also reported for tropical soils under conservation practices (Canisares et al., 2020; Villarreal et al., 2021).

Total porosity exhibited a significant increase in the OJB treatment at 20–40 cm depth in 2016, indicating an early improvement in soil structural organization associated with cover crop establishment. However, this effect was not maintained in 2021, suggesting that porosity responses may be transient or masked over time by natural soil variability and ongoing erosion–deposition processes under field conditions. These results reinforce that improvements in soil physical quality under cover crops do not necessarily follow linear or cumulative trajectories.

Despite increases in soil organic matter observed under some cover crop systems in 2021 (Table 2), aggregate stability did not differ among treatments in either evaluation year or soil layer. This finding demonstrates that, under conditions evaluated, organic matter accumulation did not translate into measurable improvements in aggregate resistance to water disruption. Although cover crops are frequently associated with enhanced aggregation through organic carbon inputs (Haruna et al., 2020; Kapur et al., 2007), aggregation processes in shallow tropical soils are strongly constrained by mineralogical composition, texture, and frequent disturbance by erosive rainfall, which may limit the expression of treatment effects within the evaluated period (Fu et al., 2020; Jiao et al., 2024; Jimenez et al., 2025).

Although cover crops increased soil organic matter in some treatments, this increase did not translate into measurable improvements in aggregate stability during the evaluated period. Soil conservation benefits were primarily associated with surface protection and erosion control rather than intrinsic aggregate resistance. Treatments without effective soil cover (BS and OBS) consistently exhibited the highest soil and water losses values in both years, highlighting the vulnerability of bare soil systems to erosion on sloping landscapes. Cover crop systems effectively reduced erosive losses by decreasing runoff velocity and

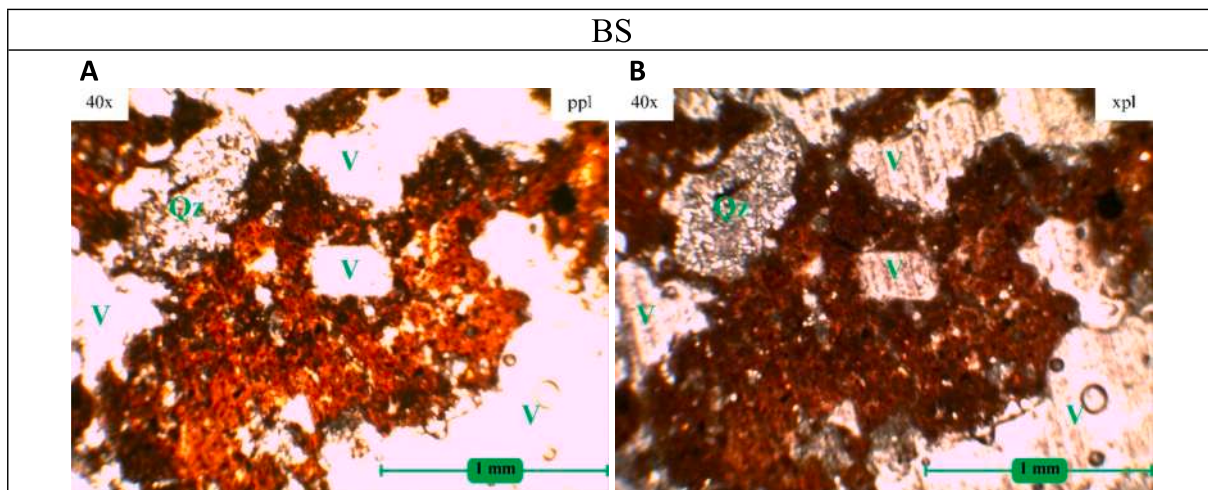


Fig. 4. Soil microstructure of BS: bare soil in 2015–2021 and fallow land in 2021–2023. A: ppl – plane-polarized light; B: xpl – cross-polarized light; Qz: quartz; V: vugh.

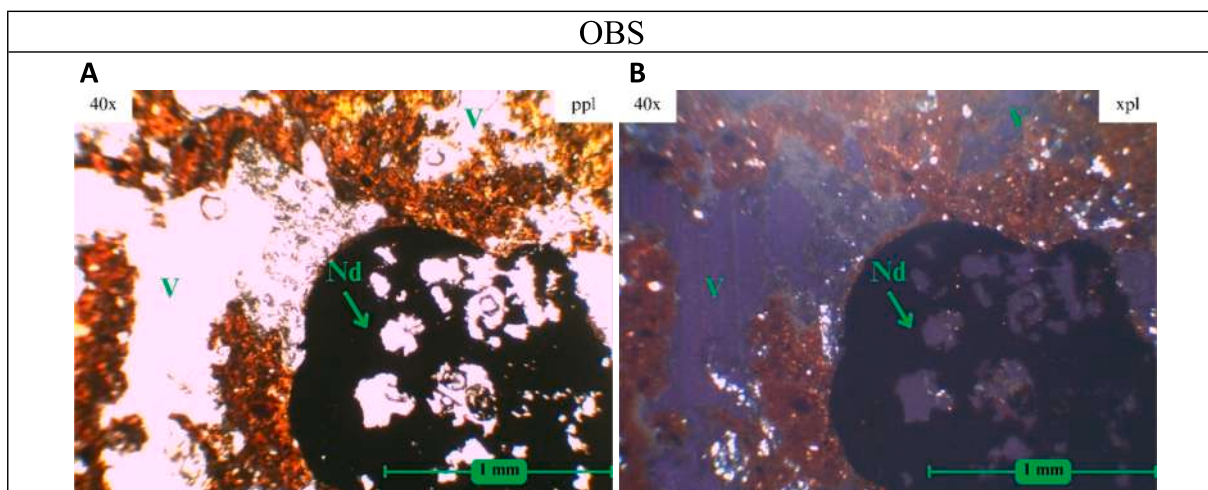


Fig. 5. Soil microstructure of OBS: olive tree on bare soil in 2015–2021 and fallow land in 2021–2023. A: ppl – plane-polarized light; B: xpl – cross-polarized light; V: vugh; Nd: nodule.

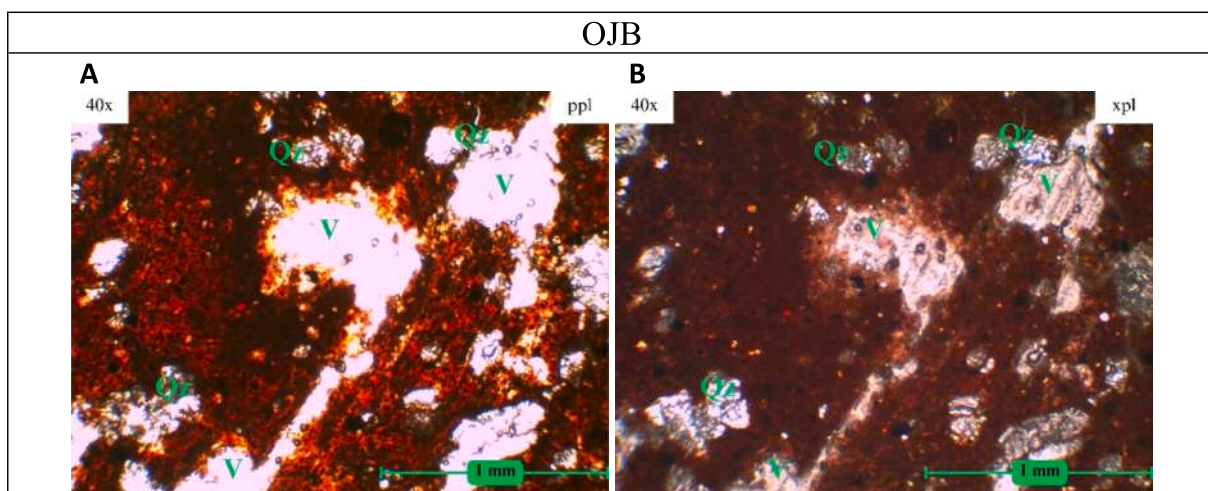


Fig. 6. Soil microstructure of OJB: olive tree intercropped with jack beans in 2015–2017, olive tree crowned intercropped with mowed spontaneous vegetation in 2017–2021, and fallow land in 2021–2023. A: ppl – plane-polarized light; B: xpl – cross-polarized light; Qz: quartz; V: vugh.

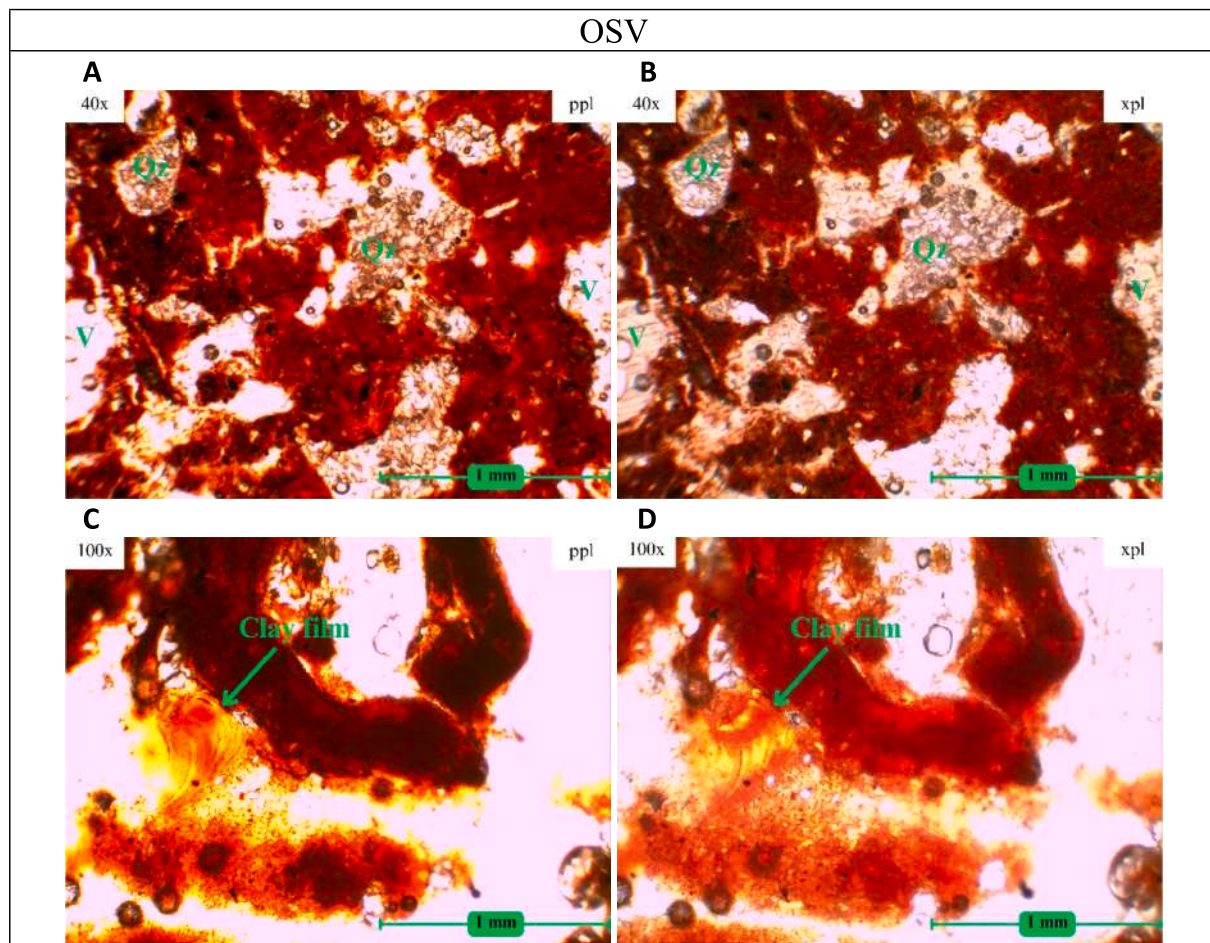


Fig. 7. Soil microstructure of OSV: olive tree intercropped with mowed spontaneous vegetation in 2015–2021 and fallow land in 2021–2023. A and C: ppl – plane-polarized light; B and D: xpl – cross-polarized light; Qz: quartz; V: vugh.

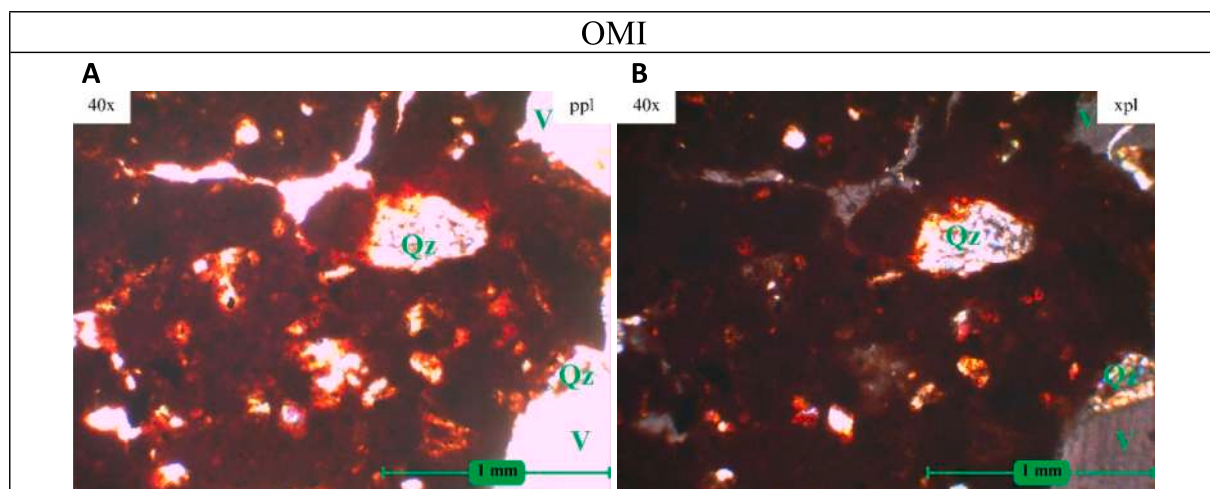


Fig. 8. Soil microstructure of OMI: olive trees intercropped with millet in 2015–2016, olive trees intercropped with sunn hemp in 2016–2017, olive trees with spontaneous vegetation treated with herbicide in 2017–2021, and fallow land in 2021–2023. A: ppl – plane-polarized light; B: xpl – cross-polarized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

dissipating rainfall energy at the soil surface (Haruna et al., 2020; Chen et al., 2020).

Among the cover crop systems, the OJB treatments showed the most consistent reduction in soil loss across evaluation years, while OSV and OMI also promoted substantial decreases in runoff and sediment

transport. These responses are consistent with previous studies in olive orchards under tropical and Mediterranean conditions, which demonstrate that vegetation cover is a dominant factor controlling erosion, even when changes in soil structural indices are limited (Zuazo et al., 2020; Beniaich et al., 2023). Together, these results indicate that erosion

control in tropical olive orchards is primarily governed by surface protection and vegetation-mediated processes rather than by intrinsic changes in aggregate stability.

4.2. Soil chemical properties

The absence of significant differences among treatments in 2016 indicates that cover crop management did not promote short-term changes in soil chemical properties, reinforcing that improvements in soil fertility under perennial systems established on shallow tropical soils require medium- to long-term implementation (Table 2). This temporal pattern has been consistently reported in long-term studies evaluating cover crop effects under perennial crops (Fageria et al., 2005).

After six years, clear effects of cover crop management on soil chemical properties were observed, particularly in the surface layer (0–20 cm). In general, treatments managed with soil cover exhibited higher soil organic matter content, carbon stock, sum of bases, and available phosphorus compared with systems without effective soil cover (bare soil). These results highlight the overall role of cover cropping in enhancing surface soil fertility, nutrient retention, and organic matter accumulation in erosion-prone olive orchards (Guimarães et al., 2021; Pareja-Sánchez et al., 2024).

When individual cover crop management systems were compared, distinct responses were observed. The OJB system promoted the highest soil organic matter content, and sum of bases, suggesting a broader improvement in soil chemical quality. This response is likely associated with the combined legacy effects of legume-derived organic inputs during the initial years and the subsequent maintenance of spontaneous vegetation, which favors continuous residue inputs and nutrient cycling.

The OSV treatment also showed high values of sum of bases, comparable to those observed under OJB, indicating that mowed spontaneous vegetation was effective in maintaining exchangeable base levels in the surface soil. Similar patterns have been reported in olive orchards where spontaneous vegetation reduced nutrient losses associated with runoff and erosion (Pareja-Sánchez et al., 2024; Brito et al., 2025).

In contrast, the OMI system showed a more specific response in relation to available phosphorus. In the 0–20 cm layer in 2021, available phosphorus values under OMI were significantly higher than those observed in the olive monoculture under bare soil (OBS), while no significant differences were detected when compared with the other cover crop management systems or bare soil without olive trees (Table 2). This indicates that the grass-legume succession adopted in the OMI systems was effective in preventing phosphorus depletion relative to bare soil conditions with olive monoculture, rather than promoting a generalized increase in phosphorus availability.

No consistent effects of cover crop management systems on soil chemical properties were observed in the 20–40 cm layer in 2021, indicating that chemical improvements were largely restricted to the surface soil, where organic inputs, root activity, and biological processes are more intense. This depth-dependent response is consistent with observations reported for tropical perennial systems under conservation management (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. Each trench evaluated was spaced approximately 6 m apart (Fig. 1), suggesting 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 a weaker structure and lighter reddish

colors. These characteristics reflect the combined effect of limited organic inputs and continuous exposure of the soil surface to erosive forces, which restrict aggregate formation and favor structural degradation. 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. The presence of vegetation cover promotes organic accumulation, root activity, and biological structuring, which contribute to enhance aggregation and horizon development over time (Melo et al., 2023; Oliveira et al., 2024).

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). This gradient reflects the cumulative effect of management history on soil surface stability, where systems providing continuous soil cover and residue input favored the preservation and vertical development of the A horizon by reducing erosion and promoting *in situ* soil formation. Although the OMI treatment used millet and sunn hemp as cover crops in the first two years of production, subsequent years saw the use of herbicide to control spontaneous vegetation, which limited the amount of vegetative material contributing to surface horizon development. This management shift helps explain the intermediate thickness of the A horizon observed under OMI relative to OJB and OSV.

The BS treatment, in addition to the low thickness of the A horizon, was 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 Dystrudepts. Cunha et al. (2019), who studied the highest parts of the Oratório stream micro-basin (Espírito Santo, Brazil), pointed out that in these regions, with predominantly mountainous to sloping and intense erosion, shallow or very shallow soils, such as Dystrudepts, are the most common. Under such conditions, inadequate soil cover accelerates truncation of surface horizons, further limiting soil depth and effective rooting volume.

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, and is 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 (Schick et al., 2000; Silva et al., 2009; Oliveira et al., 2024). In this context, the morphological differences observed among treatments illustrate how cover crop management system can partially offset inherent soil limitations by enhancing surface horizon preservation and structural expression. However, it is important to consider 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 Fig. 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, 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 thin sections (depth 0–4.3 cm) shown in Fig. 3, the OSV treatment exhibited a more pronounced reddish coloration in the upper part of the thin section, whereas the OJB treatment was virtually absent, showing a lighter color in the first 2 cm, suggesting clay migration into the lower layers. This color contrast is indicative of selective removal and redistribution of fine particles at the soil surface, a process commonly intensified under erosive conditions but partially moderated by cover crop management systems.

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 expression as a consequence of continuous organic residue inputs, active root turnover, and increased biological activity, which collectively favor aggregate stabilization, organic-mineral associations, and microscale structural reorganization. The presence of iron nodules, matrix impregnation, and root fragments in these treatments reflects enhanced redox cycling of iron, localized organic enrichment, and repeated wetting-drying cycles, which are characteristic processes of more evolved pedogenic environments in tropical Inceptisols (Anjos et al., 2025). The poro- and granostriated micromass observed under OJB and OMI indicates clay reorientation around mineral grains driven by biological aggregation pathways rather than mechanical compaction (Stoops, 2003).

In contrast, the BS and OBS treatments showed weaker micromorphological features, with minimal pedofeatures and less structural complexity. The absence of permanent soil cover increased exposure to raindrop impact and surface sealing, limiting biological activity, organic matter incorporation, and microaggregate formation (Jimenez et al., 2025). As a result, these systems exhibited simpler micromass fabrics and less development pedogenic features, reflecting a stagnation or retardation of soil-forming process under continuous erosive stress.

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, indicating a dispersed skeleton in the matrix background of clay domains, and granostriated, suggesting the orientation and compaction of clay domains around sand and gravel grains. In addition, the micaceous crystallitic fabric reflects the mineralogical inheritance from granitic parent material, particularly the abundance of mica in the fine sand and silt fraction.

In the OSV treatment, the micromass exhibited a speckled and crystalline structure, while the pedofeatures contained concentric nodules composed of illuvial clay film fragments. These features indicate active clay mobilization and short-distance redistribution within the surface layer, driven by episodic erosion and partial stabilization promoted by spontaneous vegetation system. The presence of remnant illuvial clay coatings suggests that erosion process not only result in net soil loss but also promote internal reorganization of fine particles within the profile, contributing to microstructural heterogeneity. The concentric nodules likely represent successive phases of clay deposition and reworking, reflecting alternating periods of disturbance and recovery. Thus, the OSV system represents an intermediate pedogenic condition, in which erosion-induced clay movement coexists with biological moderation, generating distinctive micromorphological signatures with functional implications for soil aggregation and pore continuity (Table 4, Fig. 7). Taken together, the micromorphological contrasts observed under different cover crop management systems provide a structural basis for the contrasting soil responses measured at the field scale, reinforcing the importance of continuous soil cover for maintaining soil integrity in tropical olive orchards.

5. Conclusions

1. Cover crop management systems significantly influenced soil structural and microstructural properties in a tropical Dystrudepts under olive cultivation. Among the evaluated systems, the association of olive trees with jack beans during the initial years, followed by the maintenance of mowed spontaneous vegetation, resulted in the most consistent multi-scale improvements, combining lower soil loss, greater thickness of the A horizon, increased total porosity, and more developed micromorphological features.
2. Different cover crop management strategies led to distinct soil responses, reflecting contrasts between surface-driven erosion control and subsurface structural modification, while bare soil systems consistently showed weaker structural expression and higher susceptibility to erosion. These results demonstrate that maintaining continuous soil cover is essential for preserving soil structure and functionality in erosion-prone olive orchards.
3. From an applied perspective, the adoption of cover crops or managed spontaneous vegetation represents an effective and practical strategy for tropical olive growers to reduce soil degradation, enhance soil physical quality, and promote long-term sustainability of orchard systems.

CRedit authorship contribution statement

Eduardo Medeiros Severo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Gabriele Medeiros Hermógenes Severo:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation. **Paul Andres Jimenez Jimenez:** Writing – original draft, Visualization, Supervision, Methodology. **Yuri Lopes Zinn:** Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization. **Bruno Montoani Silva:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Conceptualization. **Junior Cesar Avanzi:** Writing – original draft, Visualization, Validation. **Marx Leandro Naves Silva:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

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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Data availability

[Data base \(Original data\)](#) (Zenodo)

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