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Soil tillage, fertilization, and conservation practices for improving coffee yield, quality, and sustainability in Brazil

Diego Fernando Arcos Calvache
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Thesis submitted to the Soil Science and Plant Nutrition Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

Adviser: Edson Marcio Mattiello

Co-adviser: Gustavo Franco de Castro

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Aos meus amados pais Gladis Calvache e Carlos Arcos...
A meu querido irmão Carlos Arcos e sobrinhos Santiago e Renata...
A minha querida prima Andrea Romo e Salvador...
A meus queridos avos Floralba, Mercedes e Eduardo (in memoriam) ...

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ABSTRACT

CALVACHE, Diego Fernando Arcos, D.Sc., Universidade Federal de Viçosa, July, 2025. **Soil tillage, fertilization, and conservation practices for improving coffee yield, quality, and sustainability in Brazil**. Adviser: Edson Marcio Mattiello. Co-adviser: Gustavo Franco de Castro.

Coffee cultivation in Brazil occurs under a wide range of edaphoclimatic and topographic conditions, necessitating site-specific soil management strategies to ensure sustainable productivity. This doctoral thesis aimed to evaluate the effects of deep soil tillage, organic and mineral fertilization, and land-shaping practices on soil fertility, nutrient dynamics, root development, nutrient export, and coffee productivity (Coffea arabica and Coffea canephora) in different cultivars under contrasting environmental conditions. The first chapter investigated the influence of deep tillage, combined with organic and mineral fertilization, on root development, carbon dynamics, and biological activity in a cohesive soil under Coffea canephora cultivation. The results showed that deep tillage significantly promoted root system expansion, especially in deeper soil layers, increased carbon stocks, and enhanced biological activity throughout the soil profile, contributing to a more resilient rhizosphere environment. The second chapter focused on a Coffea arabica production system under both irrigated and rainfed conditions. It was observed that deep tillage, in combination with organic and mineral inputs, improved nutrient availability, enhanced soil fertility throughout the soil profile, and increased coffee yield. These findings reinforce the importance of integrating physical and nutritional soil management regardless of water availability. In the third chapter, nutrient export via harvested beans was quantified in different Coffea arabica cultivars grown in the Cerrado Mineiro. It was found that nutrient export by coffee fruits in this region is more strongly influenced by yield levels than by genotypic differences among cultivars. The final chapter presents a technical bulletin on the use of bench terraces for coffee cultivation in mountainous areas. It outlines the principles of topographic surveying, terrace design, and construction, with a focus on soil conservation practices and practical recommendations for the sustainable implementation of this technique in sloped landscapes. Taken together, the results of this thesis demonstrate that the adoption of integrated soil management practices, including deep tillage, the use of organic inputs, mineral fertilization, and conservation-oriented terracing, contributes to improved soil fertility, enhanced root performance, greater nutrient use efficiency, and sustained coffee productivity across diverse agricultural zones in Brazil.

Keywords: Coffea arabica, Coffea canephora, terracing, cattle manure, nutrient extraction

RESUMO

CALVACHE, Diego Fernando Arcos, D.Sc., Universidade Federal de Viçosa, julho de 2025. **Práticas de preparo, adubação e conservação do solo para melhorar a produtividade, a qualidade e a sustentabilidade do café no Brasil**. Orientador: Edson Marcio Mattiello. Coorientador: Gustavo Franco de Castro.

A cafeicultura no Brasil ocorre em uma ampla variedade de condições edafoclimáticas e topográficas, o que demanda estratégias de manejo do solo específicas para cada ambiente, visando à sustentabilidade da produtividade. Esta tese de doutorado teve como objetivo avaliar os efeitos do preparo profundo do solo, da adubação orgânica e mineral e das práticas de adequação do relevo sobre a fertilidade do solo, a dinâmica de nutrientes, o desenvolvimento radicular, a exportação de nutrientes em diferentes cultivares de café arábica e na produtividade do cafeeiro (Coffea arabica e Coffea canephora) em diferentes condições ambientais. O primeiro capítulo avaliou a influência do preparo profundo do solo, associado à adubação orgânica e mineral, sobre o desenvolvimento radicular, a dinâmica do carbono e atividade biológica em um solo coeso na cultura de Coffea canephora. Os resultados demonstraram que o preparo profundo favoreceu significativamente a expansão do sistema radicular, especialmente em camadas mais profundas do solo, aumentando os estoques de carbono e melhorando a atividade biológica do solo ao longo do perfil, contribuindo para um ambiente rizosférico mais resiliente. O segundo capítulo abordou um sistema de produção de Coffea arabica sob condições irrigadas e de sequeiro. Observou-se que o preparo profundo, em combinação com insumos orgânicos e minerais, promoveu maior disponibilidade de nutrientes, melhoria na fertilidade do solo ao longo do perfil do solo e aumento da produtividade do cafeeiro. Esses achados reforçam a importância da integração entre o manejo físico e nutricional do solo, independentemente da disponibilidade hídrica. No terceiro capítulo, quantificou-se a exportação de nutrientes pelos grãos colhidos em diferentes cultivares de Coffea arabica cultivadas no Cerrado Mineiro. Observou-se que A exportação de nutrientes pelos frutos do café no Cerrado Mineiro é mais fortemente influenciada pelos níveis de rendimento do que pelas diferenças genotípicas entre as cultivares. O último capítulo apresenta um boletim técnico sobre o terraceamento do tipo patamar para o cultivo de café em áreas montanhosas. São descritos os princípios para o levantamento topográfico, o traçado e a construção dos terraços, com enfoque em práticas conservacionistas do solo e recomendações práticas para a implementação sustentável dessa técnica em relevo acidentado. De forma integrada, os resultados desta tese

demonstram que a adoção de práticas de manejo integrado do solo, incluindo o preparo profundo, o uso de insumos orgânicos, a adubação mineral e o terraceamento conservacionista, contribui para a melhoria da fertilidade do solo, o desempenho radicular, a eficiência no uso de nutrientes e a manutenção da produtividade do cafeeiro em diferentes zonas agrícolas do Brasil.

Palavras-chave: Coffea arabica, Coffea canephora, terraceamento, cama de frango, esterco bovino, extração de nutrientes.

SUMÁRIO

1 INTRODUCTION

Coffee production in Brazil plays a strategic role in both the national economy and international agricultural trade, with *Coffea arabica* and *Coffea canephora* being the predominant cultivated species. The sustainability of coffee systems in the country, particularly in heterogeneous edaphoclimatic conditions such as those found in the Espírito Santo state and the Cerrado Mineiro region, depends heavily on the adoption of adequate soil and nutrient management strategies (Rodrígues-López, 2012; Silva et al.,2019).

In tropical regions, soil constraints such as high weathering, acidity, and low nutrient availability, especially in Oxisols and cohesive soils, limit root development and reduce crop resilience and productivity (Mullins et al., 1990; Fageria and Baligar, 2008). Deep soil tillage has emerged as a promising strategy to overcome subsurface compaction and structural limitations, improving the physical environment for root proliferation (Azevedo et al., 2022). Combined with the application of organic amendments, such as manure and biochar, this practice may enhance soil organic carbon, microbial activity, and nutrient availability in deeper soil layers (Wang et al., 2010; Dunjana et al., 2012).

The first study of this thesis evaluates the impact of deep soil tillage and organic–mineral fertilization on the biological quality of cohesive soils and the root architecture of *C. canephora*. Cohesive horizons are prevalent in coastal tablelands and present a significant barrier to root penetration and water infiltration (Choudhury et al., 2013). The integration of organic inputs such as poultry litter and biochar is supported by studies that report improvements in microbial activity and labile organic matter fractions in subsoils, contributing to long-term soil quality and carbon stocks (Cotrufo et., 2019; Singh et al., 2022).

The second study extends this investigation to *C. arabica* cultivated under irrigated and rainfed conditions in the Cerrado Mineiro, a region known for highly weathered soils with low natural fertility. Previous research has emphasized the relevance of subsoil amelioration through gypsum application and deep tillage to improve nutrient distribution and cation exchange capacity in deeper layers (Besen et al., 2021). Moreover, organic inputs, especially biochar and cattle manure, and mineral fertilizers have demonstrated potential in increasing pH, base saturation, and nutrient retention, while also contributing to coffee quality attributes through improved synchrony between nutrient supply and plant demand (Lehmann et al., 2011; Zhang et al., 2020).

The third study investigates nutrient export via coffee fruits across multiple *Coffea arabica* cultivars cultivated in the Cerrado Mineiro region. Understanding the quantity and distribution of exported nutrients is essential for designing site-specific fertilization strategies that prevent nutrient depletion and ensure long-term soil fertility (Garcia et al., 2009). Accurate and up-to-date data on nutrient export are crucial for improving the precision of fertilization recommendations, as they reflect the actual nutrient demand of coffee plants under modern production conditions. In fertile soils, the replacement of nutrients based on fruit export is a technically sound and environmentally sustainable approach, aligning fertilizer input with crop removal and minimizing nutrient losses (Prezotti, 2001).

Finally, a technical bulletin was developed on terracing systems for coffee cultivation in mountainous areas, providing both theoretical and practical guidelines for the design and implementation of agricultural terraces. Mountain agriculture often faces severe environmental challenges, particularly related to soil erosion and limitations on mechanization due to steep slopes (Wadt, 2004; Pruski, 2009). In this context, terracing emerges as an effective strategy to mitigate erosive processes, stabilize production systems, and optimize land use in fragile environments. Despite requiring a significant initial investment, the bulletin emphasizes short-, medium-, and long-term income generation strategies, including intercropping with annual and perennial crops and the establishment of cover crops aimed at improving the physical, chemical, and biological quality of the soil (Volk and Cogo, 2008). These practices not only contribute to soil conservation but also enhance resource use efficiency and system resilience in mountainous coffee-producing regions.

In synthesis, this thesis contributes to the scientific and practical understanding of how soil management and fertilization practices can improve coffee root development, soil fertility, carbon dynamics, and nutrient efficiency in key Brazilian coffee regions. These findings support the development of sustainable coffee systems resilient to climatic and edaphic challenges.

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Chapter 1 – Influence of deep tillage and different fertilization sources on root development and soil biological properties in *Coffea canephora* cultivation

1 ABSTRACT

The cultivation of *Coffea canephora* is a major economic driver in Espírito Santo, Brazil, where cohesive soils with physical limitations constrain root development and crop performance. This study aimed to evaluate the effects of deep soil tillage and subsurface application of mineral and organic fertilizers on soil biological quality and root development in Conilon coffee cultivation. The experiment was conducted in São Gabriel da Palha (ES), using five treatments in a randomized block design with four replications. Treatments combined two tillage depths (60 cm and 150 cm) with mineral fertilization, poultry litter, and biochar. Soil CO_2-C concentrations were measured at multiple depths (0–150 cm) using cavity ring-down spectroscopy; root traits were quantified via WinRHIZO software; and soil organic matter fractions, particulate organic matter (POM-C), mineral-associated organic matter (MOAM-C), and total soil carbon (Total-C) were analyzed. The results demonstrated that deep tillage combined with organic inputs (especially t_5: Deep soil tillage at 150 cm, mineral fertilization, poultry litter, and biochar) significantly enhanced CO_2-C emissions, root growth, and soil organic carbon stocks in subsurface layers, notably below 40 cm. This treatment also promoted the vertical redistribution of labile and stabilized organic carbon fractions, resulting in total carbon stocks of up to 204.68 Mg ha^{-1} in deeper soil layers. These findings highlight the importance of integrating deep tillage with organic amendments as a strategy to improve root penetration, biological activity, and long-term carbon sequestration in physically restrictive soils, contributing to sustainable management and productivity of Conilon coffee systems.

Keywords: Conilon coffee, cohesive soil, chicken manure, biological activity, carbon stocks

2 INTRODUCTION

Conilon coffee (*Coffea canephora*) is a vital crop for the economy of Espírito Santo, Brazil, representing a major source of income and employment for rural communities in the region. Espírito Santo is Brazil's largest Conilon coffee producer, a crop particularly suited to the region's climate and soil conditions (INCAPER, 2020). However, one of the major challenges for maximizing yield and quality in these plantations is the soil's cohesive nature, which limits root development and restricts access to deeper nutrients and water, especially beyond 50 cm depth. This limitation is primarily due to the face-to-face arrangement of clay minerals, particularly kaolinite, which creates dense soil layers resistant to root penetration (Mullins et al., 1990). Therefore, investigating management practices to address these limitations is imperative.

Deep soil tillage has gained attention due to its potential to break up cohesive soil layers, enhance root penetration, and improve the soil physical properties (Choudhury et al., 2013). However, most studies on deep tillage do not extend beyond 100 cm depth (Azevedo et al., 2023), leaving a gap in understanding the effects of soil management at depths up to 150 cm. Investigating these deeper layers is crucial, as root exploration and nutrient distribution in these zones may significantly influence crop resilience and productivity (Calvache et al., 2025). Additionally, the incorporation of organic amendments, such as biochar and poultry litter, into the tilled soil volume represents an innovative approach that could enhance soil fertility, carbon sequestration, stimulate biological activity, and create a more favorable environment for root development (Mambani et al., 1989). Further improving the effectiveness of deep tillage in Conilon coffee production. These improvements in soil quality highlight the critical role of organic matter dynamics, emphasizing the need to further explore its distinct compartments and functional roles in sustaining soil health and crop performance, particularly in response to deep tillage and organic amendments.

The dynamics of soil organic matter (SOM) play a critical role in carbon storage and soil health, particularly in response to tillage and organic amendments. Particulate organic matter (POM) a labile fraction composed of partially decomposed plant residues, contributes to short-term nutrient cycling and microbial activity, while mineral-associated organic matter (MAOM), stabilized by interactions with soil minerals, represents a long-term carbon pool resistant to decomposition (Cotrufo et al., 2019). The balance between POM and MAOM influences carbon sequestration potential across soil depths, with MAOM dominating in deeper

soil layers due to mineral interactions (Lavallee et al., 2020). Understanding how deep tillage and organic inputs alter these fractions is essential for predicting their impact on carbon stocks and long-term soil fertility (Sokol et al., 2019).

Building on the importance of soil organic matter (SOM) dynamics in response to tillage and organic amendments, it's crucial to consider the composition and behavior of SOM fractions. SOM consists of fractions that vary in their physical and chemical properties, as well as their turnover rates (Lavallee et al., 2020). Understanding the dynamics of these SOM fractions is essential for developing more sustainable environmental practices (Cambardela & Elliot, 1992). Furthermore, when biological activity is higher, as in soils with larger microbial populations or increased root activity, CO_2 production is elevated (Six et al., 2006). These higher CO_2 levels can aid in the dissolution of mineral compounds in the soil, releasing previously unavailable nutrients for plant uptake (Osanai et al., 2015). Consequently, elevated CO_2 concentrations typically indicate a more biologically active soil environment, with enhanced organic matter decomposition, microbial respiration, and nutrient mineralization processes (Wang et al., 2014).

This study aims to evaluate the effects of deep tillage on biological activity, root development, and soil organic matter composition across various soil depths. By examining the CO_2 concentration at different depths, quantifying root characteristics, and fractionating organic matter into particulate (POM) and mineral-associated organic matter (MAOM), we assess the potential of deep tillage combined with organic amendments, such as poultry litter and biochar, to enhance soil conditions for Conilon coffee growth.

3 MATERIAL AND METHODS

3.1 Experimental arrangement

The experiment was conducted in São Gabriel da Palha, Espírito Santo, Brazil (19°01'00" S, 40°32'11" W, at 118 m elevation). The site's soil is classified as a (densic) Xanthic hapludox (Soil Survey Staff, 2022), with a gently undulating relief (approximately 8 % slope). The region has an Aw-type climate according to Köppen's classification (Köppen, 1936), characterized by a dry winter (April–September) with precipitation below 60 mm, and a rainy summer (October–March) averaging 150 mm of rainfall per month.

Prior to establishing the experiment, soil samples were collected from six soil layers: 0–10, 10–20, 20–40, 40–60, 60–100, and 100–150 cm. These samples were subjected to chemical and physical characterizations, which are summarized in Table 1.

The study was set up in a simple arrangement, with five treatments combining soil tillage and fertilization:

t_1: Soil tillage at 60 cm depth and standard fertilization;

t_2: Soil tillage at 60 cm depth, mineral fertilizer, poultry litter and biochar;

t_3: Deep soil tillage at 150 cm depth and mineral fertilization:

t_4: Deep soil tillage at 150 cm, mineral fertilizer, and poultry manure;

t_5: Deep soil tillage at 150 cm, mineral fertilizer, poultry manure, and biochar.

A randomized complete block design was employed, with four replicates and one coffee clone per block. Clones 02, LB1, P1, and 13 were selected based on their documented productivity and favor among regional producers. Each experimental unit consisted of a single row with seven plants, spaced 1 × 1 m apart. The central three constituted the designated useful plot.

3.2 Soil tillage and fertilization

Conventional soil tillage for coffee planting was done by subsoiling at a depth of 60 cm. For deep soil tillage, a backhoe was used to dig trenches 80 cm wide and 150 cm deep (Figure 1)

Table 1. Chemical and physical soil characteristics of (densic) Xanthic hapludox before planting coffee.

Depth	**pH**	**P**	**K**	**S**	**Ca^{2+}**	**Mg^{2+}**	**Al^{3+}**	**HAl**	**CEC**	***c*P-rem**	**Mn**	**B**	**Cu**	**Zn**	**MO**	**Sand**	**Silt**	**Clay**	**Bd**
cm	H_2O	.....mg dm^{-3}.....			.....$cmol_c$ dm^{-3}.....					mg L^{-1}	.....mg dm^{-3}.....				g kg^{-1}	.....%.....			kg dm^{-3}
0.0–10	5.58	13.50	105.00	3.10	2.63	0.92	0.00	3.60	7.42	40.10	31.80	0.85	0.37	2.07	27.10	49.10	1.70	49.20	1.42
10–20	4.89	10.40	31.00	0.10	1.18	0.30	0.10	3.20	4.76	39.90	9.20	0.77	0.31	1.16	14.90	41.60	6.00	52.40	1.49
20–40	4.48	3.50	19.00	2.80	1.13	0.28	0.39	2.90	4.36	33.50	2.30	0.50	0.22	0.27	10.90	36.40	1.30	62.30	1.55
40–60	4.27	1.00	4.00	6.60	0.94	0.19	0.69	3.40	4.54	31.40	1.30	0.45	0.23	0.35	10.90	32.00	2.00	66.00	1.41
60–100	4.27	0.80	4.00	13.80	0.86	0.17	0.69	2.60	3.64	28.10	1.40	0.45	0.32	0.27	8.10	31.60	3.00	65.40	1.49
100–150	4.13	2.20	2.00	34.20	0.53	0.19	0.69	2.60	3.33	26.80	2.50	0.45	0.32	0.39	5.40	29.90	2.20	68.00	1.33

pH in water (L:S 2.5 L kg^{-1}); exchangeable Ca^{2+}, Mg^{2+}, Al^{3+} in a 1 mol L^{-1} KCl soil extract; available P, K, Mn, Cu and Zn extracted by Mehlich 1; available S extracted by monocalcium phosohate 500 mg L^{-1} P in 2 mol L^{-1} acetic acid; B extracted by hot water; H+Al extracted by Calcium acetate 0.5 mol L^{-1}, pH 7.0; CEC = Cations Exchange Capacity; *c*P-rem = Remaining phosphorus. Particle size analysis with the pipette; SOM = Soil Organic Matter by Walkley-Black method; Bd = bulk density, by volumetric ring method. Source: Calvache et al. (2025).

The biochar utilized in this study was produced from eucalyptus biomass, and after being triturated, it presented a density of 0.55 kg dm^{-3}. The granulometry of the biochar was as follows: > 4 mm: 11.9 %, 2-4 mm: 15 %, 1-2 mm: 12.7 %, 1-0.25 mm: 27.4 %, and < 0.25 mm: 33.1 %.

The poultry litter initially had a water content of 59 % and, after drying, its density reached 0.5 kg dm^{-3}. Table 2 shows the nutrient contents of both the poultry litter and biochar.

For the planting phase, specific amounts of lime, gypsum, poultry litter, biochar, and fertilizers were used (Table 3). These correctives, along with the mineral and organic fertilizers, were uniformly mixed into the soil and returned to the trench, ensuring even distribution, and preventing the formation of depressions that could lead to water accumulation and potentially drowning.

Table 2. Nutrient content of poultry litter and biochar

	C	N	P	K	Ca	Mg	S	B	Mn	Fe	Al
	……..…… g kg^{-1} ……..…….										
Poultry litter	250	21	4.7	16.9	7.3	4.4	2.9	0.024	0.584	1.43	-
Biochar	69	0.7	0.21	0.45	2.4	0.28	0.11	0.007	0.055	0.32	0.62

Source: Calvache et al., (2025)

Table 3. Quantities of limestone, gypsum, poultry litter, biochar, and fertilizers to be used in coffee planting

Treatments[1]	Tillage	Limestone	Gypsum	Poultry litter	Biochar	SS[2]	P-Reactive	MAP[3]	Urea	KCl[3]	Ulexita	ZnO
		…….. kg m^{-1} ……..			L m^{-1}	…….....…….. g m^{-1} ……...……..						
t_1	Conventional	0.3	0.15	0.5	-	150	200	-	-	-	-	-
t_2	Conventional	0.8	0.3	2.5	12	50	321	212	178	133	4.43	1.6
t_3	Deep + Mineral	2.4	0.9	-	-	50	962	635	533	400	13.3	4.8
t_4	Deep + Mineral + Poultry litter	2.4	0.9	7.5	-	50	962	635	533	400	13.3	4.8
t_5	Deep + Mineral + Poultry litter + Biochar	2.4	0.9	7.5	36	50	962	635	533	400	13.3	4.8

t_1 = Soil tillage at 60 cm depth and standard fertilization; t_2 = Soil tillage at 60 cm depth, mineral fertilizer, poultry litter, and biochar; t_3 = Deep soil tillage at 150 cm depth and mineral fertilization; t_4 = Deep soil tillage at 150 cm depth, mineral fertilizer, and poultry litter; t_5 = Deep soil

tillage at 150 cm depth, mineral fertilizer, poultry litter, and biochar. SSP = Simple superphosphate. MAP = Monoammonium phosphate. KCl = Potassium chloride. Source: Calvache et al. (2025)

3.3 Planting and irrigation

In December 2017, the seedlings were initially planted with a spacing of 3 x 1 m. However, the specific arrangement varied depending on the tillage treatment. In the cases of deep tillage (t_3, t_4, and t_5), each plant was allocated a volume of prepared soil measuring 1200 dm^{-3} (8 x 10 x 15 dm: width, length, and depth). On the other hand, for the conventional tillage treatments (t_1 and t_2), the soil volume per plant was approximately 150 dm^{-3} (3 x 10 x 5 dm: width, length, and depth).

The irrigation system utilized was micro spray, delivering water at a rate of 14 L $hour^{-1}$ $plant^{-1}$.

3.4 Assessments

Gas samples were collected three years after planting to evaluate biological activity. The first collection (A) was conducted in February 2018, the second collection (B) in July 2019, and the third collection (C) in February 2020. It was utilized 50 mm PVC tubes specifically designed for gas collection, strategically placed within each experimental plot at depths of 0–20, 20–40, 40–60, 60–80, 80–120, and 120–150 cm, as illustrated in Figure 1. Gas samples were gathered from the top of each tube using syringes connected to hoses attached to the respective soil layers. CO_2 concentrations were then quantified using cavity ring-down spectroscopy (CRDS, Picarro G2131–i), in the laboratory.

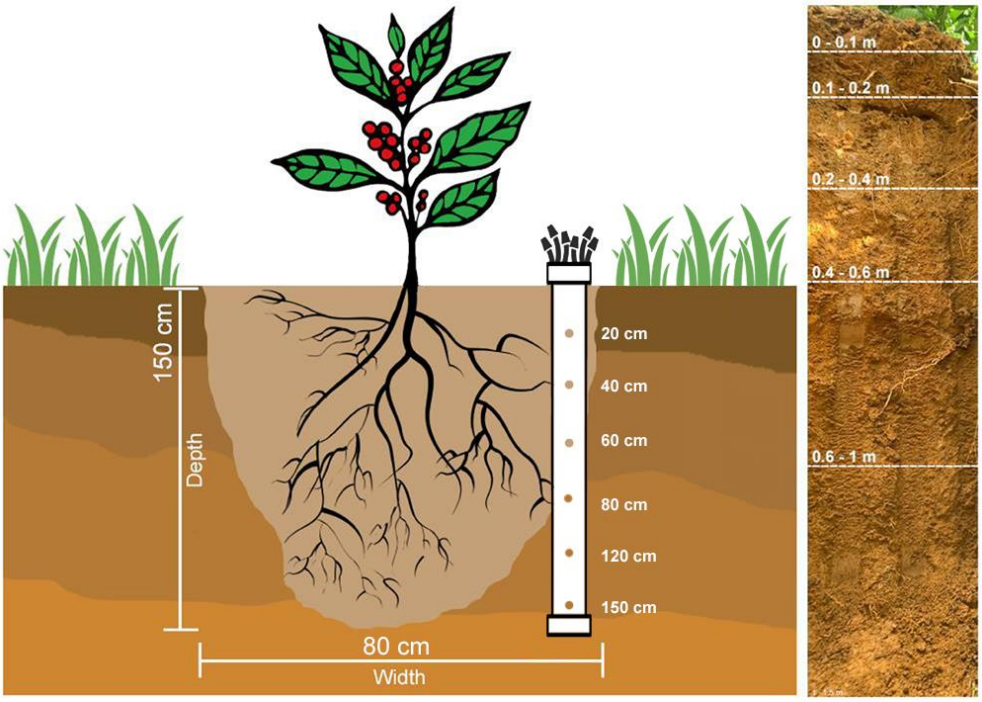


Figure 1. Diagram showing the installation of PVC pipes for gas sampling at soil depths of 0-20, 20-40, 40-60, 60-80, 80-120, and 120-150 cm.

Soil samples were collected along the coffee planting lines at five depths: 0–10, 10–20, 20–40, 40–60, and 60–100 cm to assess root development. Samples were taken with a soil auger, obtaining 100 cm^3 of soil at the first depth, 200 cm^3 at the next three depths, and 400 cm^3 at the last. The soil was air–dried, and all roots presents were collected and stored in a 20 % alcohol solution. Using the WinRHIZO software, parameters such as root volume, surface area, root projection, root tips, and forks were evaluated.

For the fractionation of soil organic matter, including particulate organic matter (POM) and mineral–associated organic matter (MAOM) following the methodology described by Cambardella and Elliot (1992), soil samples were collected at depths of 0–10, 10–20, 20–40, 40–60, and 60–100 cm. The fractions were separated using sodium hexametaphosphate. The material was transferred to a 300 mL container and passed through a 0.05 mm sieve, where the fraction that passed through the sieve was classified as MAOM, and the material retained on the sieve corresponded to POM. The samples were then oven–dried at 60 °C, sieved through a 100-mesh sieve, and analyzed with a CHNS elemental analyzer to determine the carbon concentrations in each fraction.

The soil organic carbon (SOC) stock was calculated for each soil layer (0-10, 10-20, 20-40, 40-60, 60-100 cm) using the following equation (Ellert & Bettany, 1995):

SOC Stock (Mg ha^{-1}) = SOC (g kg^{-1}) × Bulk Density (kg dm^{-3}) × Thickness (m) × 10

Where:

SOC = Soil organic carbon concentration (g kg^{-1});

Bulk Density (Ds) = Soil bulk density (kg dm^{-3});

Thickness (Ts) = Thickness of the soil layer (m);

10 = Conversion factor to express results in Mg ha^{-1}.

Bulk density values were obtained from pre-planting soil characterization (Table 1), ensuring consistency with initial soil conditions.

4. RESULTS

4.1 The CO2-C concentrations

The CO_2-C concentration increased along the soil profile, reaching its peak in the 60–150 cm soil layers. The highest CO_2-C concentrations were observed in the first sampling time in the deep soil tillage treatments (t_3, t_4, and t_5) across the soil profile. These samples, collected in February 2019 during the summer, showed notable differences below a depth of 60 cm, with conventional soil tillage treatments (t_1 and t_2) recording CO_2-C concentrations of 16719.1 ppm while deep soil tillage treatments reached 30852.3 ppm. The highest values (26272.2 and 30852.3 ppm) were observed in t_4 and t_5, which received organic amendments in the form of poultry litter and a combination of poultry litter and biochar, respectively (Table 4).

In contrast, during the second year of collection (July 2019, winter), lower CO_2-C concentrations were observed compared to the first collection conducted in the summer of the first year after planting. However, increases in CO_2-C concentrations were noted along the soil profile. t_2 recorded the lowest CO_2-C concentrations below 60 cm depth, except at 120 cm. On the other hand, t_5 with deep soil tillage and combination of poultry litter and biochar, showed the highest CO_2-C concentrations, with a value of 16257.9 ppm, which was considerably higher compared to treatment 2, which registered CO_2-C concentrations of 10451.9 ppm (Table 4).

In the third year of collection (February 2021, summer), the results showed an increase in CO_2-C concentration compared to the previous year, with notable differences observed at a depth of 60–80 cm between treatments with deep soil tillage (t_3, t_4, and t_5) and those with conventional soil tillage (t_1 and t_2). Similarly, the results indicated higher concentrations at a depth of 120–150 cm in treatments with deep soil tillage. Treatment 5, which included deep soil tillage and the addition of organic inputs, recorded a CO_2-C concentration of 26,222 ppm, while treatment 2, with conventional soil tillage, recorded a concentration of 23,665 ppm (Table 4).

Table 4. CO_2 concentration (ppm) measured at six soil depths (0-20, 20-40, 40-60, 60-80, 80-120, and 120-150 cm) at three intervals after planting: one year (Period A), two years (Period B), and three years (Period C).

Treatment	Depth(cm)											
	0.0 - 20		20 - 40		40 - 60		60 - 80		80 - 120		120 - 150	
	Period A											
t_1	1359.9	a	2705.0	a	5149.9	a	8741.6	bc	12053.5	b	19984.2	ab
t_2	1297.0	a	2719.6	a	4840.3	a	5075.7	c	12382.1	b	16719.1	b

t_3	2694.9	a	3842.5	a	8312.1	a	12937.4	ab	18833.9	ab	22573.2	ab
t_4	1619.6	a	5204.4	a	9538.5	a	14850.9	a	16933.5	ab	26272.2	a
t_5	2215.8	a	4661.5	a	7869.0	a	12527.0	ab	22287.1	a	30852.3	a
Period B												
t_1	2189.3	a	4351.3	a	7822.9	a	10570.5	a	10359.8	a	13744.1	ab
t_2	1372.7	a	4316.4	a	5322.0	a	4353.1	b	11178.0	a	10451.9	b
t_3	1781.5	a	3378.4	a	7526.5	a	10278.3	a	11512.7	a	13911.5	a
t_4	990.3	a	3661.9	a	6941.7	a	9365.2	a	12232.5	a	14424.2	a
t_5	2556.8	a	2854.3	a	7337.1	a	8518.7	a	12223.9	a	16257.9	a
Period C												
t_1	3648.8	a	6194.4	a	12817.4	a	13752.8	a	23044.7	a	23800.8	a
t_2	1777.0	a	6442.9	a	10378.6	a	14569.0	a	20585.0	a	23665.3	a
t_3	3588.2	a	5519.4	a	13837.0	a	20254.3	a	26499.3	a	24965.7	a
t_4	1469.1	a	5739.9	a	12600.8	a	19742.3	a	22977.7	a	26844.6	a
t_5	1969.2	a	7023.5	a	13375.1	a	18858.4	a	21747.1	a	26222.4	a

t_1 = Tillage subsoiling at 50 cm, producer control; t_2 = Tillage subsoiling with mineral fertilization, poultry litter, and biochar; t_3 = Deep soil tillage at 150 cm and mineral fertilization; t_4 = Deep soil tillage at 150 cm, mineral fertilization, and poultry litter; t_5 = Deep soil tillage at 150 cm, mineral fertilization, poultry litter, and biochar. Different letters denote significant differences among land-uses within each season by the Tukey's test (α=0,05).

4.2 Root development

Root development was assessed across five soil depth intervals. While no significant differences ($p > 0.05$) were observed in the upper 40 cm soil layer, marked variations emerged at greater depths (60-100 cm). Conventional tillage treatments consistently showed reduced root system development, with significantly lower values ($p < 0.05$) for all measured variables: root volume, surface area, projected area, root tips, and root forks. In contrast, treatments incorporating deep tillage with organic amendments (t_4 and t_5) exhibited superior root development, demonstrating significant increases in the variables evaluated compared to conventional tillage (Table 5). These results suggest deep tillage practices combined with organic inputs significantly enhance root proliferation in subsurface soil layers.

At the 20-40 cm depth interval, treatment t_3 (deep tillage without organic inputs) consistently demonstrated the poorest root development across all evaluated variables. This treatment yielded significantly lower values ($p < 0.05$) than comparative treatments, including the smallest root volume (0.34 cm^3), lowest root surface area (277.13 cm^2), minimal projected

root area (88.21 cm^2), fewest root tips (1,093), and least branching frequency (634 forks). These results suggest that deep tillage alone, without organic amendment incorporation, may negatively impact root system development in this critical subsurface layer.

The root evaluation at 60 – 100 cm depth, and the conventional soil tillage treatment with no organic inputs (t_1) showed the lowest results across the evaluated parameters. In contrast, the treatment with deep soil tillage and the incorporation of poultry litter and biochar demonstrated significant improvements in the parameters being assessed, with a root volume of 1.67 cm^3, a surface area of 1509.03 cm^2, a root projection of 480.34 cm^2, 7776.58 root tips, and 6051 forks.

Table 5. Variables for evaluating root development in a (densic) Xanthic Distrudox (Soil Survey Staff, 2022) up to 100 cm deep.

Treatment [(1)]	Depth	Root Volume		Surface Area		Root Projection		Tips		Forks	
	cm	cm^3				cm^2					
t_1	0 – 10	1.13	a	958.02	a	304.95	a	2679.67	a	2360.67	a
t_2	0 – 10	1.03	a	902.00	a	287.11	a	3263.00	a	2317.75	a
t_3	0 – 10	0.71	a	669.95	a	213.25	a	2491.25	a	1654.25	a
t_4	0 – 10	0.94	a	847.38	a	269.73	a	4041.75	a	2554.50	a
t_5	0 – 10	1.59	a	1473.67	a	469.09	a	6354.33	a	5845.00	a
t_1	10 – 20	0.58	a	526.07	a	167.45	a	1864.75	a	1399.75	a
t_2	10 – 20	0.64	a	611.14	a	194.53	a	2133.75	a	1541.25	a
t_3	10 – 20	0.44	a	338.91	a	107.88	a	1177.50	a	1012.75	a
t_4	10 – 20	0.88	a	801.26	a	255.05	a	3752.50	a	2538.00	a
t_5	10 – 20	0.49	a	563.03	a	179.22	a	2256.00	a	1305.33	a
t_1	20 – 40	1.01	ab	761.52	ab	242.40	ab	3055.67	ab	2653.67	ab
t_2	20 – 40	1.51	a	1110.27	a	353.41	a	4636.50	ab	5047.00	ab
t_3	20 – 40	0.34	b	277.13	b	88.21	b	1093.25	b	634.25	b
t_4	20 – 40	1.43	ab	1345.55	a	428.30	a	6604.33	a	6753.00	a
t_5	20 – 40	0.89	a	595.95	ab	192.20	ab	1658.00	ab	1463.00	ab
t_1	40 – 60	0.72	a	485.10	a	303.48	a	2152.25	a	1325.00	a
t_2	40 – 60	0.98	a	893.55	a	274.42	a	3073.75	a	2792.75	a
t_3	40 – 60	0.89	a	459.94	a	146.40	a	1966.75	a	994.25	a
t_4	40 – 60	0.43	a	423.74	a	134.88	a	2203.50	a	1617.75	a
t_5	40 – 60	0.66	a	627.20	a	199.64	a	3031.67	a	1865.67	a
t_1	60 – 100	0.68	b	461.38	b	146.93	b	1795.00	b	1215.00	b
t_2	60 – 100	0.70	b	591.46	ab	187.74	ab	2386.00	b	1550.00	b

t_3	60 – 100	1.49	b	865.96	ab	275.64	ab	2823.33	b	2821.33	ab
t_4	60 – 100	0.87	a	801.73	ab	255.20	ab	4254.75	a	2766.50	ab
t_5	60 – 100	1.67	a	1509.03	a	480.34	a	7776.58	a	6051.89	a

(1) t_1: Tillage subsoiling at 50 cm, producer control; t_2: Tillage subsoiling with mineral fertilization, poultry litter, and biochar; t_3: Deep soil tillage at 150 cm and mineral fertilization; t_4: Deep soil tillage at 150 cm, mineral fertilization, and poultry litter; t_5: Deep soil tillage at 150 cm, mineral fertilization, poultry litter, and biochar. Different letters denote significant differences among land-uses within each season by the Tukey's test (α=0,05).

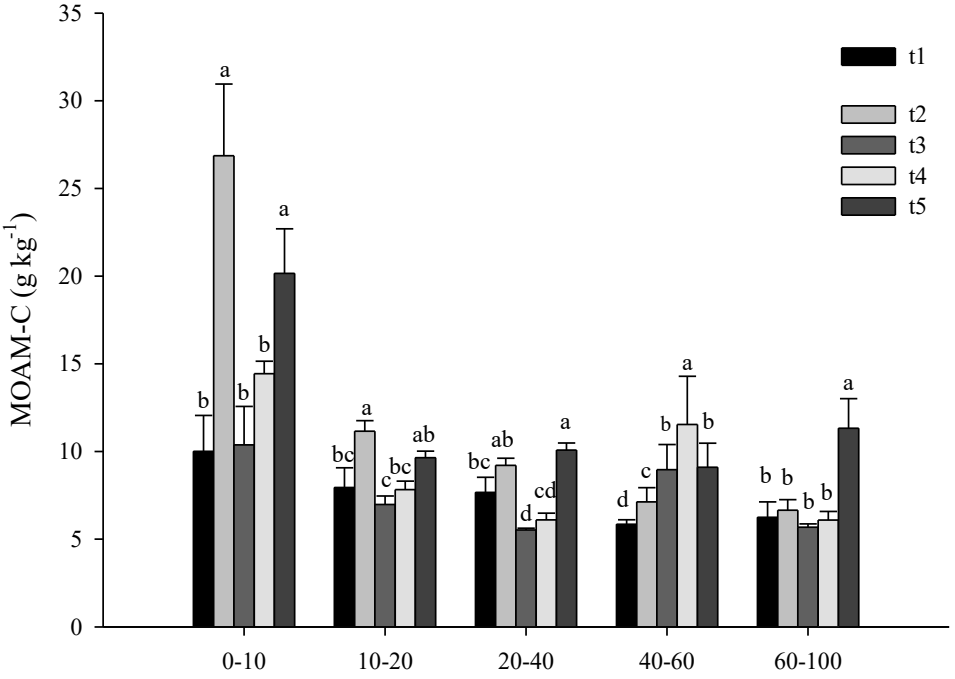
4.3 Dynamics of soil organic matter fractions

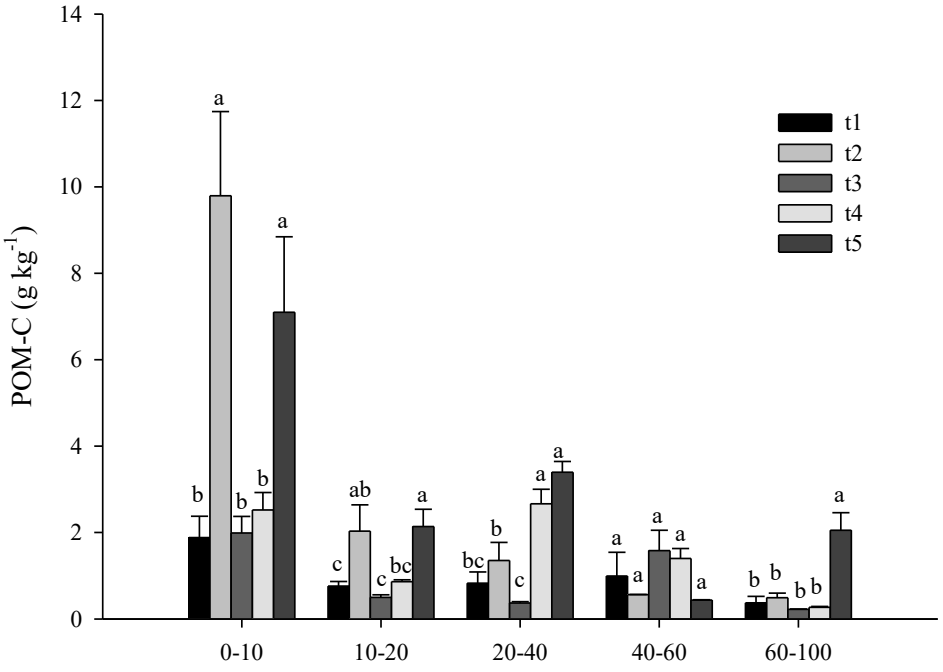
The POM-C fraction in the treatments with adding poultry litter and biochar (t_2 and t_5) was significantly higher in the surface soil layer (0–10 cm), reaching 9.79 and 7.10 g kg^{-1}, respectively. A similar behavior was observed in the 10–20 cm layer, where t_5 showed significant differences compared to the other treatments, except for t_2, with values of 2.14 and 2.03 g kg^{-1}, respectively. In the 20–40 cm layer, treatments t_4 and t_5, which involved deep soil tillage and organic input, exhibited the highest carbon contents, recording values of 2.67 and 3.40 g kg^{-1}, respectively. In the 60–100 cm layer, t_5, combining deep soil tillage, poultry litter, and biochar, presented significantly higher carbon levels compared to other treatments, reaching 2.80 g kg^{-1} (Figure 2).

The MOAM-C fraction in the treatments with adding of poultry litter and biochar (t_2 and t_5) was significantly higher in the surface soil layer (0–10 cm), reaching 26.86 and 20.16 g kg^{-1}, respectively. In the 10–20 cm layer, the MOAM carbon content in t_2 was significantly higher than in the other treatments, except for t_5, reaching values of 11.16 and 9.65 g kg^{-1}, respectively. In the 20–40 cm layer, t_5 showed a significantly higher MOAM carbon content compared to the other treatments, except for treatment 2, with values of 10.08 and 9.22 g kg^{-1}, respectively. Finally, in the 60–100 cm layer, t_5 had a significantly higher carbon content, reaching 11.33 g kg^{-1}.

The total carbon content analysis revealed distinct treatment effects across soil depths. In surface layers (0-20 cm), treatments t_2 and t_5 showed the highest carbon concentrations (36.47 and 27.26 g kg^{-1} at 0-10 cm; 13.19 and 11.79 g kg^{-1} at 10-20 cm, respectively), reflecting the positive impact of poultry litter and biochar incorporation. In subsurface layers (20-100 cm), treatments combining deep tillage with organic inputs (t_4 and t_5) demonstrated significantly higher carbon accumulation, particularly at 40-60 cm (t_4: 12.94 g kg^{-1}; t_5: 9.54 g kg^{-1}) and 60-100 cm (t_5: 13.38 g kg^{-1}). These results highlight that while

surface carbon enrichment was achieved through organic amendments alone, combining deep tillage with carbon inputs (t_5) proved most effective for enhancing carbon storage throughout the soil profile, promoting vertical carbon redistribution to deeper layers.





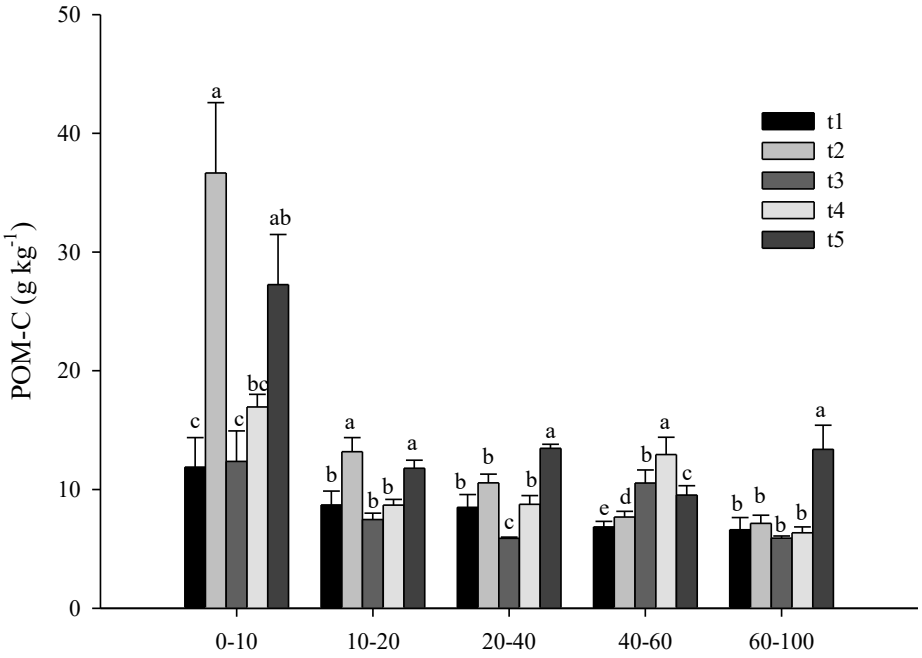


Figure 2. Soil organic matter fractions, the organic C associated with organic material retained in the 53 μm sieve corresponds to POM-C and that associated with the silt + clay minerals fraction corresponds to MAOM-C and Total-C, measured at five soil depths (0-10; 10-20; 20-40; 40-60 and 60-100 cm). Different letters denote significant differences among land-uses within each season by the Tukey's test (α=0,05). t_1 = Tillage subsoiling at 50 cm, producer control; t_2 = Tillage subsoiling with mineral fertilization, poultry litter, and biochar; t_3 = Deep soil tillage at 150 cm and mineral fertilization; t_4 = Deep soil tillage at 150 cm, mineral fertilization, and poultry litter; t_5 = Deep soil tillage at 150 cm, mineral fertilization, poultry litter, and biochar. Means with the same letter do not differ by Tukey's test ($p < 0.05$)

4.4 SOC stocks

The results of soil organic carbon (SOC) stocks indicate that the application of organic amendments led to increased carbon accumulation, particularly in treatments receiving poultry litter and biochar. In the surface layers (0–20 cm), t_2 and t_5, incorporating these organic inputs, presented the highest SOC stocks, reflecting the contribution of labile and partially stabilized organic matter in the upper soil profile. Notably, a distinct pattern emerged below 20 cm: treatment t_5, which included deep tillage combined with poultry litter and biochar, exhibited a significant increase in carbon stocks in subsurface layers, reaching 79.74 Mg ha^{-1} at 60–100 cm. This highlights the effectiveness of deep incorporation of carbon-rich amendments in

overcoming physical limitations associated with cohesive soils, thereby enhancing carbon sequestration at depth (Figure 3).

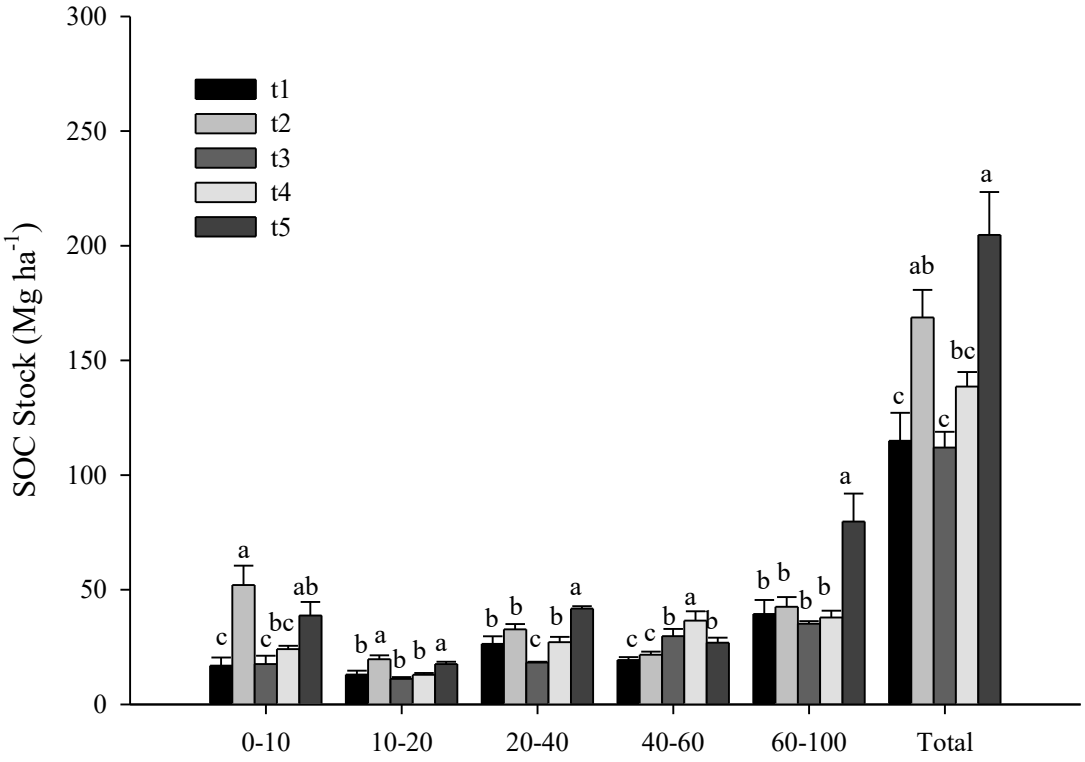


Figure 3. Soil organic carbon stocks measured at five soil depths (0-10, 10-20, 20- 40, 40-60, and 60-100 cm), and total organic carbon stocks in the soil profile. Different letters denote significant differences among land-uses within each season by the Tukey's test (α=0,05). t_1 = Tillage subsoiling at 50 cm, producer control; t_2 = Tillage subsoiling with mineral fertilization, poultry litter, and biochar; t_3 = Deep soil tillage at 150 cm and mineral fertilization; t_4 = Deep soil tillage at 150 cm, mineral fertilization, and poultry litter; t_5 = Deep soil tillage at 150 cm, mineral fertilization, poultry litter, and biochar. Means with the same letter do not differ by Tukey's test ($p < 0.05$)

5. DISCUSSION

The results demonstrate that deep soil tillage, particularly when combined with organic amendments such as poultry litter and biochar, significantly affects multiple interrelated soil processes. Among these, CO_2-C concentrations (as a proxy for microbial respiration), root development, organic matter fractionation (POM-C and MOAM-C), and carbon stocks throughout the soil profile are critically enhanced. This improves the soil's physical, chemical, and biological properties over time (Premalatha et al., 2023). Similar results were observed by Babu et al., (2023), who reported that soil tillage with biochar can lead to increased CO_2 concentrations in deeper soil layers.

The elevated CO_2-C concentrations observed in deeper soil layers, particularly in t_5, can be attributed to enhanced microbial activity stimulated by increased root exudation result deep tillage combined with organic amendments. Root exudates act as readily available carbon substrates, promoting microbial respiration and reshaping microbial community structures, thereby accelerating the decomposition of soil organic matter in subsoil layers (Yonemura et al., 2009; Xu et al., 2020). This mechanism is consistent with the findings of Lei et al. (2023), who highlighted the pivotal role of root exudates in mediating both the input and efflux of soil carbon. Similarly, Adamczyk et al. (2021) demonstrated that adding root exudates significantly increases soil respiration and modifies microbial communities, even under cold alpine conditions. Furthermore, Wen et al. (2022) emphasized that the specific chemical composition of exudates can differentially influence microbial activity and carbon mobilization, underscoring the complexity of root-microbe-soil interactions in regulating carbon dynamics. Complementary evidence from Kim et al. (2020) also indicates that the structure and function of soil microbiomes are highly responsive to management practices such as cover cropping and soil disturbance, suggesting that deep tillage and organic matter incorporation can markedly affect microbial-mediated carbon processes throughout the soil profile.

Seasonal dynamics were also observed throughout the experimental period. In the first year after planting (Period A, summer 2019), CO_2-C concentrations were significantly higher in deep tillage treatments due to increased temperatures and microbial activity, which favor organic matter decomposition (Xiao, 2015; Sui et al., 2024). During the following year's winter (Period B, winter 2020), overall CO_2-C concentrations declined, likely due to lower microbial metabolism under reduced temperatures (Blume et al., 2002). However, deep tillage treatments, especially t_5, sustained relatively elevated CO_2-C levels, suggesting that the

combination of deep soil disturbance and organic inputs fosters a more resilient microbial community that maintains carbon turnover even under suboptimal conditions.

This trend became more pronounced in the third year (Period C, February 2021), when CO_2-C concentrations increased again, particularly in deeper layers (60–150 cm), reinforcing the long-term effects of deep tillage and organic matter incorporation. Applying of biochar may contribute to this persistence by improving soil structure, enhancing water retention, and providing a habitat for microbial colonization, which collectively support microbial stability and long-term carbon cycling (Johnson et al., 2017). In this context, conservation-oriented soil management enriched with organic inputs has proven effective in maintaining microbial functionality and sustaining CO_2-C fluxes across temporal and spatial gradients (Kim et al., 2020; Xiao, 2015).

The analysis of root development at different depths highlights the influence of soil preparation systems and the addition of organic inputs on plant root architecture. According to the results, no significant differences were observed up to a depth of 40 cm. However, from 60 cm onwards, differences between treatments became evident, with conventional soil tillage resulting in lower root development. In contrast, deep tillage and organic inputs favored greater root growth. The limitation of root development in conventionally managed soils may be associated with soil compaction and lower macropore availability, reducing water infiltration and aeration, as Lipiec et al. (2012) observed. Restricting root growth under these conditions can compromise water and nutrient uptake in deeper layers, negatively impacting plant performance (Bengough et al., 2011).

At a depth of 20–40 cm, the treatment with deep soil tillage but without organic inputs (t_3) exhibited reduced root development compared to other treatments, suggesting that the absence of organic matter limited improvements in soil structure and root proliferation, as described by Six et al. (2002). At the 60–100 cm depth, root development was also more limited treating conventional soil tillage and no organic inputs (t_1). In contrast, root development was more pronounced in the treatment with deep tillage and adding poultry litter and biochar (t_5). These findings indicate that incorporating organic matter into the soil enhances porosity, moisture retention, and nutrient availability, thereby promoting deeper and more extensive root growth, as Lehmann et al. (2011) reported. This supports previous research on the role of soil management in enhancing root development and improving plant resource acquisition (Jin et al., 2013).

The results indicate that adding poultry litter and biochar significantly influenced the carbon associated with particulate organic matter (POM-C) and mineral-associated organic

matter (MOAM-C) across different soil depths. These two fractions represent functionally distinct pools of soil organic carbon, each with specific stabilization mechanisms and implications for carbon persistence (Six et al., 2002; Cotrufo et al., 2013; Lavallee et al., 2020).

The dynamics of particulate organic matter carbon (POM-C), a labile fraction derived from plant residues with relatively rapid turnover, were markedly influenced by adding organic inputs, particularly in surface and subsurface layers. In the 0–10 cm layer, t_2 and t_5 exhibited the highest POM-C contents, a pattern consistent with the increased supply of labile substrates provided by poultry litter, which stimulates microbial activity and aggregation processes that promote the physical protection of particulate matter (Lal, 2016; Wander, 2004; Plaza-Bonilla et al., 2013). Although biochar is more recalcitrant, its application improves soil structure and creates favorable microhabitats, indirectly enhancing POM stabilization (Lehmann et al., 2011). The persistence of high POM-C values in the 10–20 cm layer under t_5 suggests the downward movement and physical retention of organic residues, likely mediated by bioturbation and root activity, and reinforced by the formation of macroaggregates, which protect organic particles from microbial attack (Castellano et al., 2015; Lee et al., 2021). At greater depths (20–40 cm and 60–100 cm), treatments involving deep tillage and biochar addition (t_4 and t_5) sustained elevated POM-C levels, indicating that soil disturbance can incorporate organic materials into deeper horizons, while biochar contributes to carbon stabilization through physical entrapment and the provision of microsites that support microbial activity and aggregate formation (Novak et al., 2009; Brodowski et al., 2007; Kuzyakov et al., 2009).

The MOAM-C fraction, recognized for its long residence time due to strong physicochemical interactions with mineral surfaces, responded positively to the combined application of poultry litter and biochar, particularly under treatments t_2 and t_5, which exhibited the highest values in the surface layer (0–10 cm). This result reflects the synergistic effect of organic inputs in promoting microbial activity and saturating mineral surfaces with microbial-derived carbon compounds (Six et al., 2002; Cotrufo et al., 2013). Poultry litter provides readily available substrates that are microbially transformed into stabilized organo-mineral complexes, while biochar modifies soil chemical properties, such as pH and cation exchange capacity, and enhances the sorption of dissolved organic matter, thereby favoring mineral-associated carbon formation (Sun et al., 2022). Notably, in deeper layers (20–40 cm and 60–100 cm), t_5 maintained superior MOAM-C contents, indicating that deep soil loosening facilitates vertical redistribution and the formation of stable complexes, a process further reinforced by the reactive surfaces and porous nature of biochar (Baldock & Skjemstad, 2000; Poeplau & Don, 2015).

These findings support the microbial efficiency–matrix stabilization (MEMS) framework, whereby microbial by-products from fresh inputs are selectively stabilized through sorption onto mineral phases (Cotrufo et al., 2013). Thus, the strategic integration of organic amendments and deep tillage emerges as an effective approach to enhance both labile and stable organic carbon pools, contributing to nutrient cycling and long-term carbon sequestration throughout the soil profile (Lavallee et al., 2020; Rumpel & Kögel-Knabner, 2011).

When considering the total organic carbon (Total-C), which encompasses both particulate organic matter carbon (POM-C) and mineral-associated organic matter carbon (MOAM-C), the significant increases observed in treatment t_5, particularly in subsurface layers (40–100 cm), align with the patterns found for each fraction. The elevated Total-C in these depths indicates that the simultaneous enhancement of labile and stable carbon pools through organic amendments and deep tillage leads to effective carbon accumulation below the plow layer. This pattern mirrors the SOC stock increases observed in treatment t_5, suggesting that the redistribution and stabilization of particulate and mineral-associated carbon significantly contribute to deep carbon storage (Lavallee et al., 2020; Rumpel & Kögel-Knabner, 2011). The synergistic input of biochar and poultry litter enhances microbial transformation of organic matter and promotes its protection via aggregation and sorption, resulting in a vertically integrated increase in soil carbon pools. As such, this integrated management strategy not only boosts carbon inputs but also facilitates their long-term stabilization across soil horizons, reaffirming its relevance for sustainable soil carbon sequestration in physically constrained systems (Lehmann & Joseph, 2024; Paustian et al., 2016; Jobbágy & Jackson, 2000).

6. CONCLUSION

The results of this study demonstrate that soil tillage methods and the addition of organic amendments significantly influenced soil CO_2-C concentration. Deep soil tillage treatments showed higher CO_2-C concentrations over time, particularly in layers below 60 cm, suggesting that this practice can enhance microbial activity and organic matter decomposition at greater depths. The observed seasonal variation indicates that environmental factors, such as temperature, also play a crucial role in CO_2-C dynamics in the soil. Additionally, combining deep soil tillage with organic inputs, such as poultry litter and biochar, showed potential for promoting organic matter stabilization and sustained CO_2 release over the years. These findings highlight the importance of soil management strategies that consider both soil quality improvement and the sustainability of the carbon cycle.

The combination of deep soil tillage with organic amendments (particularly poultry litter and biochar) not only increased labile carbon (POM-C) in surface layers but also enhanced the accumulation of mineral-associated organic carbon (MOAM-C) in deeper soil horizons. This suggests a dual mechanism of organic carbon stabilization, via physical protection in aggregates and organo-mineral interactions, promoting both short- and long-term carbon sequestration throughout the profile.

Integrating deep tillage and organic matter inputs represents a promising approach for managing cohesive soil under perennial crips such as coffee. By enhancing root development, nutrient availability, and SOC stabilization at depth, this strategy supports both agricultural productivity and climate-resilient soil carbon management.

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Chapter 2 – Deep soil tillage and organic–mineral fertilization enhance productivity and soil fertility in irrigated and rainfed *Coffea arabica*

1. ABSTRACT

The productivity and quality of coffee (*Coffea arabica*) are strongly influenced by soil physical and chemical conditions, particularly in weathered soils such as Oxisols of the Brazilian Cerrado. This study aimed to evaluate the effects of different soil management strategies, conventional (60 cm) and deep tillage (150 cm), combined with mineral fertilization, cattle manure, and biochar on soil fertility, nutrient dynamics, and *Coffea arabica* quality and productivity under irrigated and non-irrigated regimes. The experiment was conducted over a five-year period and used a split-plot arrangement within a randomized complete block design with four replicates. The main plots (Factor A) included six treatments: t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar. The subplots (Factor B) comprised two irrigation regimes: with and without irrigation. The results demonstrated that deep soil tillage significantly improved subsoil fertility by increasing pH, reducing acidity, and enhancing organic matter, calcium, magnesium, phosphorus, and potassium throughout the profile, especially in treatments t_5 and t_6. Micronutrient availability (Zn, B, Mn, and Fe) also improved under deep tillage. These treatments led to higher base saturation (> 60 %) and greater cation exchange capacity down to 150 cm depth. Regarding productivity, deep tillage practices resulted in yield increases of up to 28% (bags ha^{-1}) compared to conventional systems. Additionally, the irrigation regime positively influenced productivity, reflecting variations in yield performance across five harvests. Regarding quality, higher cupping scores were associated with more ripe fruits in deep tillage and organic amendment treatments, indicating that improved root environment and nutrient availability favor uniform fruit maturation. Overall, integrating deep tillage and organic amendments is a promising strategy for enhancing root zone fertility, maximizing yield potential, and improving beverage quality in *Coffea arabica* cultivation.

Keywords: Coffee, soil fertility, organic amendments, coffee quality.

2. INTRODUCTION

Coffee cultivation is one of Brazil's most significant agricultural activities, both economically and socially, the world's leading producer and exporter of coffee (CONAB, 2023). To ensure sustainability and increase productivity, it is essential to understand and properly manage the limiting factors affecting coffee development, particularly those related to soil fertility and water availability (Chemura et al., 2014).

In regions such as the Brazilian Cerrado, coffee cultivation faces challenges due to the predominance of highly weathered Oxisols, characterized by low natural fertility, high acidity, and chemical limitations in deeper layers (Schaefer et al., 2008). Soil management plays a crucial role in building productive environments, directly influencing nutrient availability, soil physical structure, and biological activity (Cardoso et al., 2013). Strategies such as deep soil tillage have been investigated as promising alternatives to overcome subsurface fertility constraints by improving nutrient distribution and promoting deeper root growth (Zhang et al., 2020). Furthermore, the incorporation of soil amendments and organic residues, such as cattle manure and biochar, has shown positive effects on chemical soil attributes, including increases in organic matter content, cation exchange capacity, and base saturation (Lehmann et al., 2011).

In addition to nutrient availability, water supply is a crucial factor for the successful cultivation of coffee, particularly in regions with pronounced dry seasons or irregular rainfall patterns (Mantovani and Soares, 2003). Irrigation systems have been widely adopted to stabilize yield and improve bean quality (Fernandes et al., 2020). However, appropriate soil management practices, such as deep soil tillage, adequate use of lime and gypsum, balanced mineral fertilization, and incorporating organic materials, can significantly enhance soil structure and rooting depth, promoting greater water retention and uptake efficiency (Silva et al., 2019).

A similar study conducted in the state of Espírito Santo evaluated the effects of deep soil tillage combined with organic and mineral fertilization on the productivity of Conilon coffee grown in soils with cohesive properties. The results demonstrated positive impacts of deep tillage on the physical and chemical attributes of the soil, leading to significant increases in crop productivity (Calvache et al., 2025). Based on these findings, it becomes relevant to investigate whether similar practices can yield comparable benefits for Arabica coffee cultivation under different edaphoclimatic conditions, such as those in the Cerrado Mineiro region, where soils exhibit more favorable physical characteristics.

This study aimed to evaluate the influence of different soil preparation systems, conventional and deep tillage combined with organic and mineral fertilization, on soil fertility attributes along the profile, nutrient availability, and the productivity and quality of *Coffea arabica* cultivated under irrigated and non-irrigated conditions.

3. MATERIAL AND METHODS

3.1 Experimental arrangement

The experimental site is situated in the municipality of Rio Paranaiba, Minas Gerais state, Brazil (19°10'35.1" S, 46°6'19.3" W, altitude 1058m). The soil at the site is classified as a Typic hapludox, as defined by the Soil Survey Staff (2022). The Köppen climate classification indicates that the region has a tropical Aw type (Köppen, 1936), with a dry winter season from April to September and an average precipitation rainfall of less than 33 mm, and a rainy summer season from October to March with an average rainfall of 200 mm

Before initiating the experimental protocol (December 2018), soil samples were collected from the following layers: 0-0.1, 0.1-0.2, 0.2-0.4, 0.4-0.6, 0.6-1.0, and 1.0-1.5 m. These samples were then subjected to chemical and physical analyses, the results of which are outlined in Table 1.

Table 1. Chemical and physical characteristics of Typic hapludox before the coffee planting.

Depth	**pH**	**P**	**K**	**S**	**Ca^{2+}**	**Mg^{2+}**	**H + Al**	**T**	**t**	**SOM**	***c*P-rem**	**Zn**	**B**	**Mn**	**Fe**	**Sand**	**Silt**	**Clay**	**Bd**	**V**
m	H_2O	… mg dm^{-3}...			….....cmolc dm^{-3}….....					g kg^{-1}	mg L^{-1}	..... mg dm^{-3}….....				….... %			kg dm^{-3}	%
0- 0.1	6.4	4.2	67.0	2,9	4.03	1.58	3.4	9.2	5.8	44.3	17.1	4,9	0,3	24.4	32.3	27.9	19.2	53.0	1.16	63
0.1-0.2	6.4	1.9	62.0	2,9	3.0	1.19	3.4	7.8	4.4	39.1	15.3	3	0,2	15.8	28.4	26.7	15.0	58.0	1.1	56
0.2-0.4	6.2	0.2	12.0	8,1	1.4	0.44	2.8	4.7	1.9	20.9	8.5	0,38	0,1	1.9	25.2	-	-	-	-	40
0.4-0.6	6.0	0.1	7.0	15	0.83	0.27	2.7	3.9	1.1	18.3	4.7	0,15	0,1	1.2	22.3	22.5	16.0	61.0	1.08	29
0.6-1.0	5.6	0.1	7.0	18	0.53	0.25	2.0	2.8	0.8	13	3.4	0,54	0.0	0.8	19.7	21.8	13.1	65.0	1.03	28
1.0-1.5	5.8	0.2	4.0	25	0.27	0.16	1.6	2.1	0.4	10.4	2,8	0,29	0.0	0.7	18.0	22.7	12.3	65.3	1.02	22

pH in water (L:S 2.5 L kg^{-1}); exchangeable Ca^{2+}, Mg^{2+}, Al^{3+} in 1 mol L^{-1} KCl soil extract; available P, K, Mn, Fe, Cu and Zn extracted by Mehlich 1; available S extracted by monocalcium phosphate 500 mg L^{-1} P in 2 mol L^{-1} acetic acid; B extracted by hot water; H + Al extracted by Ca acetate 0.5 mol L^{-1}, pH 7.0; T= cation exchange capacity; *c*P-rem = Remaining phosphorous; SOM = soil organic matter by Walkley-Black method; Bd= bulk density, by core method; Particle size analysis with the pipette method; V = base saturation.

The experiment was conducted in a split-plot design within a randomized complete block design with four replicates. The main plots (Factor A) consisted of six soil management treatments:

t_1 = Soil tillage at 60 cm depth and standard fertilization;

t_2 = Soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar;

t_3 = Soil tillage at 60 cm depth, standard fertilization, and gypsum amendment;

t_4 = Deep soil tillage at 150 cm depth and mineral fertilization;

t_5 = Deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure;

t_6 = Deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar.

The subplots (Factor B) included two irrigation regimes: with irrigation and without

Each experimental unit consisted of a row with thirteen coffee plants, spaced at 0.6 m. The five central plants were used as a useful plot for data collection to avoid edge effects. A total of 48 experimental units were established (6 soil treatments × 2 irrigation regimes × 4 replicates).

3.2 Soil Tillage and Fertilization

Conventional soil tillage for coffee planting was performed by subsoiling at a depth of 60 cm. For deep soil tillage, a backhoe was used to dig trenches 80 cm wide and 150 cm deep (Figure 1)

Figure 1. Deep soil tillage at 80 cm wide and 150 cm deep.

The biochar used in this study was produced from eucalyptus biomass, and following a process of trituration, it exhibited a density of 0.55 kg dm^{-3}. The granulometry of the biochar is delineated as follows: > 4 mm: 11.9 %, 2-4 mm: 15 %, 1-2 mm: 12.7 %, 0.2-1 mm: 27.4 %, and < 0.25 mm: 33.1 %. The cattle manure sample initially had a moisture content of 59 %, and following the drying process, its density reached 0.5 kg dm^{-3}. The nutrient contents of both cattle manure and biochar are presented in Table 2.

Table 2. Nutrient content of cattle manure and biochar.

	C	N	P	K	Ca	Mg	S	B	Mn	Fe	Al
						g kg^{-1}					
Cattle Manure	312	25	9.5	23.8	20.9	9.9	10.7	0.032	0.490	5.6	1.93
Biochar	69	0.7	0.21	0.45	2.4	0.28	0.11	0.007	0.055	0.32	0.62

Specific amounts of limestone, gypsum, cattle manure, biochar, and fertilizers were utilized during the planting phase, as delineated in Table 3. These corrective measures, along with mineral and organic fertilizers, were uniformly mixed into the soil and reintroduced into the trench, ensuring uniform distribution and preventing the formation of depressions that could potentially result in water accumulation and subsequent drowning.

Table 3. Quantities of limestone, gypsum, cattle manure, biochar, and fertilizer used at coffee planting.

Treatment	Limestone	Gypsum	Cattle manure	Biochar	MAP	Yara M café	P-reative	NPK	SSP	Ulexita	ZnO	CuO
	…… kg m $^{-1}$……			L m $^{-1}$	…… g m $^{-1}$……							
t_1			1.48					260	260			
t_2	1.0	0.5	2.5	12	107	300	320			4.0	2.0	1.0
t_3	0.9	6.0	1.0		50	50	200			1.33	0.4	0.2
t_4	3.0	1.5	7.5		322	1000	960	100		13.0	5.0	2.0
t_5	3.0	1.5	7.5		322	1000	960	100		13.0	5.0	2.0
t_6	3.0	1.5	7.5	36	322	1000	960	100		13.0	5.0	2.0

t_1 = soil tillage at 60 cm depth and standard fertilization; t_2= soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth, mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar. MAP = monoammonium phosphate. SSP = simple superphosphate. Yara M café = 5 % N– 35 % P – 6 % K + 9 % Ca + 0,3 % Zn + 0,3 % B

3.3 Planting and irrigation

In December 2018, the seedlings were planted with a 3.8 × 0.6 m spacing. For the deep tillage (t_4, t_5, and t_6), each plant was allocated a volume of prepared soil measuring 1200 dm^{-3} (80 × 100 × 150: width, length and depth). Conversely, for the conventional tillage

treatments (t_1, t_2, and t_3), the soil volume per plant was approximately 150 dm $^{-3}$ (30 × 100 × 50: width, length, and depth).

The irrigation system was a micro-sprinkler system, which delivered water at 2 L h^{-1} per plant. During the implementation phase, all treatments received the same amount of water. However, in the development phase (two years after planting), the experiment was divided into non-irrigated and irrigated treatments. The coffee variety planted was Acauã Novo.

3.4 Assessments

Soil samples were collected nine months after planting. These samples were collected across various depths: 0-0.2, 0.2-0.4, 0.4-0.8, 0.8-1.0, and 1.0-1.5. Leaf samples collected in February 2021 were subject to plant tissue analysis. Nutritional diagnosis was performed using the Diagnosis and Recommendation Integrated System (DRIS) and the Balanced Indexes of Kenworthy (BIK) methods, as outlined in Table 4. The NUTRICAFÉ-UFV system (Leite et al., 2009) was employed, utilizing the criteria established for *Coffea arabica*.

Gas samples were collected one year after planting to evaluate biological activity. The collection was conducted in February 2019. We utilized 50 mm PVC tubes specifically designed for gas (CO_2) collection, strategically placed within each experimental plot at depths of 0–20, 20–40, 40–60, 60–80, 80–120, and 120–150 cm, as illustrated in Figure 2. Gas samples were gathered from the top of each tube using syringes connected to hoses attached to the respective soil layers. CO_2 concentrations were then quantified using cavity ring-down spectroscopy (CRDS,Picarro G2131-i).

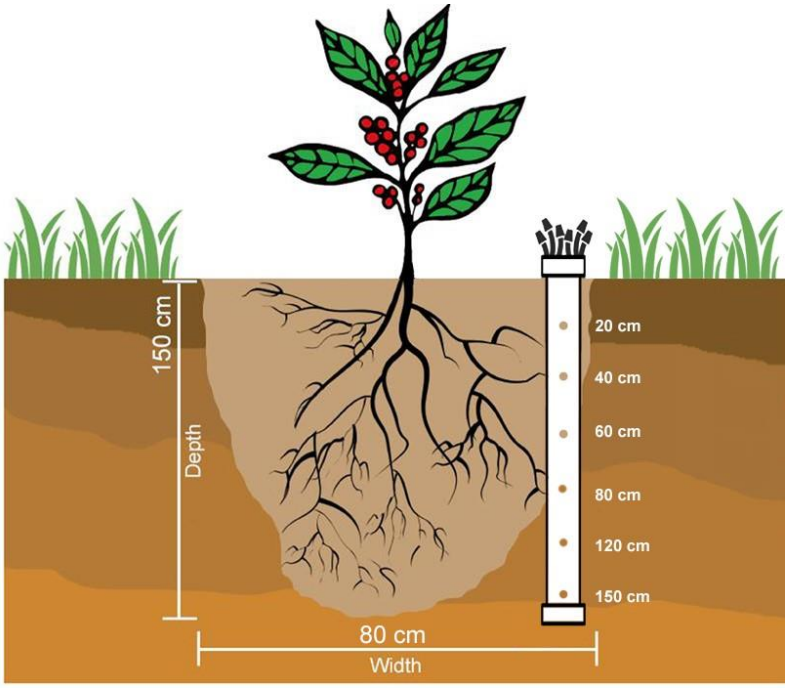


Figure 2. Diagram showing the installation of PVC pipes for gas sampling at soil depths of 0-20, 20-40, 40-60, 60-80, 80-120, and 120-150 cm.

3.5 Coffee yield

From 2021 to 2025, five coffee harvests were carried out, and the yield of ripe coffee cherries was assessed using the five central plants within each experimental unit. The yield was estimated by volume of coffee in liters per hectare (L ha^{-1}) and processed coffee in 60 kg bags per hectare (bags ha^{-1}). To determine the yield in bags ha^{-1}, coffee bean samples were collected at harvest, with one sample per treatment (four repetitions). Each sample consisted of 1 liter of coffee beans, which were naturally dried until reaching the ideal moisture content for processing. Since the standard moisture content for yield calculation is 12 %, samples with higher moisture levels were adjusted to this standard before the final yield estimation.

3.6 Coffee quality

At harvest time, fruit ripeness was assessed using a 500 mL graduated cylinder, in which the percentage of green, ripe (cherry), and overripe (raisin) coffee fruits was determined. Subsequently, 1-liter samples of harvested fruits were collected from each treatment and submitted for sensory quality analysis. The sensory evaluation of coffee quality was conducted

by a certified Q Grader, accredited by the Brazil Specialty Coffee Association (BSCA, 2024), following the standard protocol for specialty coffee assessment.

3.7 Statistical analysis

Statistical differences in coffee yield were assessed using analysis of variance (ANOVA) appropriate for a split-plot design, after verifying the assumptions of normality and homogeneity of variances. Significance levels of $p < 0.10$, $p < 0.05$, and $p < 0.01$ were considered. The main effects of soil tillage systems (factor A), irrigation (factor B), and their interaction (A × B) were evaluated. When significant effects were observed, the means were compared using Tukey's Honestly Significant Difference (HSD) test at the 5% probability level ($\alpha = 0.05$).

4. RESULTS

4.1 Chemical characteristics of the soil

Before planting, the soil exhibited pH values below of 40 cm, with a minimum value of 5.6 (Figure 3). However, the implementation of deep soil tillage, especially in treatments t_5 and t_6, increased pH levels above six throughout the soil profile. Conversely, in treatments with conventional tillage (t_1 and t_2), pH increases were observed above 80 cm, while in deeper layers, no significant increase was detected. The only exception was t_3 (conventional tillage + gypsum application), which showed higher pH increases throughout the soil profile.

The treatments with high limestone rates (t_4, t_5, and t_6) showed lower potential acidity (H+Al) values throughout the soil profile, being lower than the values observed before planting. On the other hand, in treatments with conventional tillage, an increase in potential acidity was observed below 60 cm depth (Figure 3).

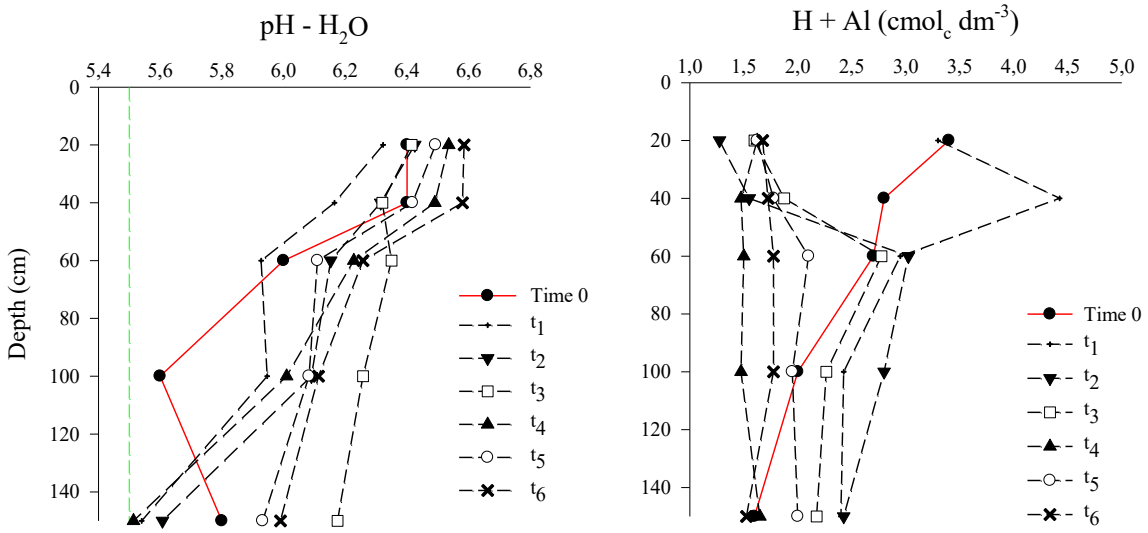


Figure 3. pH in H_2O and potential acidity (H + Al) along the profile, at time 0 and 9 months after planting. The green line represents the critical level. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar.

The results of soil chemical analysis conducted nine months after planting (Table 4) indicate a more consistent distribution of P, K, Ca, and Mg throughout the soil profile when using deep soil tillage as opposed to conventional tillage methods.

Table 4. Chemical characteristics of soil (Typic Hapludox) nine months after coffee planting.

Treatment	Depth	pH	P	K	Ca^{2+}	Mg^{2+}	H + Al	T	t	P-rem	MOS	B	Fe	Mn	Zn	V
										mg L^{-1}	g kg^{-1}					
	m	H_2O	.. mg dm^{-3}..		……. cmolc dm^{-3}…….							……. mg dm^{-3}…….				%
	0.0- 0.2	6.03	55.48	70.50	5.11	0.96	3.30	9.54	6.24	14.95	35.40	1.84	31.68	19.50	3.65	65.33
	0.2-0.4	5.64	53.10	59.33	6.57	0.89	4.40	12.14	7.72	21.35	35.30	2.19	46.98	20.28	9.94	61.83
t_1	0.4-0.6	5.81	9.58	48.00	2.77	0.85	3.00	6.69	3.74	12.35	29.30	1.74	31.53	8.20	1.39	55.95
	0.6-1.0	5.87	3.10	46.00	1.68	0.48	2.40	4.71	2.28	6.28	21.30	1.05	36.08	3.88	0.85	48.00
	1.0-1.5	5.34	0.23	37.75	0.77	0.26	2.40	3.52	1.12	3.90	16.30	0.18	33.15	1.83	0.27	32.23
	0.0- 0.2	6.61	82.80	91.00	9.00	1.39	1.30	11.90	10.63	17.55	39.90	0.86	26.65	20.80	4.42	88.68
	0.2-0.4	6.67	35.10	89.50	6.43	1.20	1.60	9.41	7.86	15.80	42.00	1.30	26.95	18.63	4.46	83.40
t_2	0.4-0.6	5.97	2.05	64.00	3.11	0.60	3.00	6.90	3.87	10.38	26.90	1.24	35.98	8.35	1.27	54.73
	0.6-1.0	5.81	1.60	92.25	1.96	0.56	2.80	5.56	2.76	7.45	22.30	1.13	38.80	5.10	1.05	48.10
	1.0-1.5	5.24	0.20	74.50	0.92	0.30	2.40	3.84	1.42	4.80	17.30	0.26	37.68	2.70	0.46	36.73
	0.0- 0.2	6.68	42.60	82.25	4.86	1.41	1.60	8.08	6.48	11.65	35.30	0.80	27.73	26.65	4.54	80.38
	0.2-0.4	6.66	52.00	66.50	5.34	1.27	1.90	8.65	6.77	12.03	37.0	0.78	25.93	17.60	2.98	76.30
t_3	0.4-0.6	6.19	1.40	43,00	2.24	0.77	2.80	5.90	3.12	10.43	27.60	0.45	35.90	10.15	1.13	53.18
	0.6-1.0	6.07	0.35	39.50	1.29	0,38	3.90	5.67	1.77	6.40	21.60	0.23	33.78	4.25	0.61	37.73
	1.0-1.5	5.51	0.15	22.25	0.86	0,25	2.20	3.34	1.16	3.70	17.00	0.16	35.73	2.25	0.53	35.08
	0.0- 0.2	6.47	11.38	50.50	3.31	0,66	1.60	5.73	4.10	6.73	24.90	1.03	26.35	12.35	1.95	71.40
	0.2-0.4	6.49	8.88	40.75	3.14	0,66	1.50	5.38	3.91	6.45	23.00	0.43	27.70	9.20	1.37	73.08
t_4	0.4-0.6	6.54	36.55	40.25	2.86	0,73	1.50	5.18	3.68	6.33	23.90	0.35	26.88	9.13	1.45	70.53
	0.6-1.0	6.55	24.63	43.75	3.09	0,72	1.50	5.40	3.92	6.43	24.00	0.34	28.78	9.18	2.00	72.30
	1.0-1.5	6.33	81.68	38.50	3.80	0,67	1.70	6.23	4.58	7.03	22.60	0.95	31.03	9.23	2.00	69.53
	0.0- 0.2	6.56	18.95	41.75	3.98	0,86	1.60	6.56	4.94	8.53	28.00	0.90	31.23	16.83	3.06	75.13
	0.2-0.4	6.41	17.38	41.00	3.54	0,91	1.80	6.33	4.56	8.58	28.30	0.64	35.15	15.15	3.08	71.60
t_5	0.4-0.6	6.22	29.18	38.75	3.08	0,84	2.10	6.12	4.02	8.18	26.90	1.14	27.40	8.93	3.02	66.40
	0.6-1.0	6.07	6.10	44.50	2.39	0,64	2.00	5.09	3.14	6.43	22.60	1.49	30.93	7.05	2.04	62.18
	1.0-1.5	6.11	42.65	75.00	3.05	0,76	2.00	6.00	4.00	6.68	24.90	1.12	31.48	7.70	4.74	65.35
	0.0- 0.2	6.43	23.90	45.00	3.57	0,85	1.70	6.20	4.53	9.23	29.30	1.03	26.18	13.63	2.54	72.63
	0.2-0.4	6.42	22.43	47.75	3.42	0,77	1.70	6.04	4.31	8.10	27.00	1.39	29.45	12.43	5.09	71.40
t_6	0.4-0.6	6.32	8.08	57.25	2.78	0,71	1.80	5.42	3.64	6.25	26.30	0.88	20.95	10.30	1.86	67.40
	0.6-1.0	6.27	18.08	59.00	2.85	0,81	1.80	5.58	3.81	7.25	24.00	0.75	30.65	9.25	2.92	67.90
	1.0-1.5	6.34	15.98	75.50	2.99	0,82	1.50	5.52	4.00	6.95	22.00	0.50	33.08	10.60	1.95	71.58

Soil samples were collected in September 2019. pH in water (L:S 2.5 L kg^{-1}); exchangeable Ca $^{2+}$. Mg $^{2+}$. Al $^{3+}$ in 1 mol L^{-1} KCl soil extract; available P. K. Mn. Cu and Zn extracted by Mehlich 1; B extracted by hot water; H + Al extracted by Ca acetate 0.5 mol L^{-1}. pH 7.0; T=

cation exchange capacity; *c*P-rem = Remaining phosphorous; SOM = soil organic matter by Walkley-Black method; Bd= bulk density, by core method; Particle size analysis with the pipette method; V = base saturation.

The deep soil tillage treatments exhibited higher Ca and Mg levels throughout the soil profile, highlighting the positive impact of lime incorporation as a nutrient source. This result is consistent with the higher pH levels observed in the soil profile, particularly in treatments 5 and 6. On the other hand, Ca levels in the conventional tillage treatments (t_1, t_2, and t_3), did not reach the critical level. For Mg, although deep soil tillage treatments showed greater uniformity along the profile, they also failed to reach the critical level, suggesting a possible underestimation of lime requirements under these conditions (Figure 4).

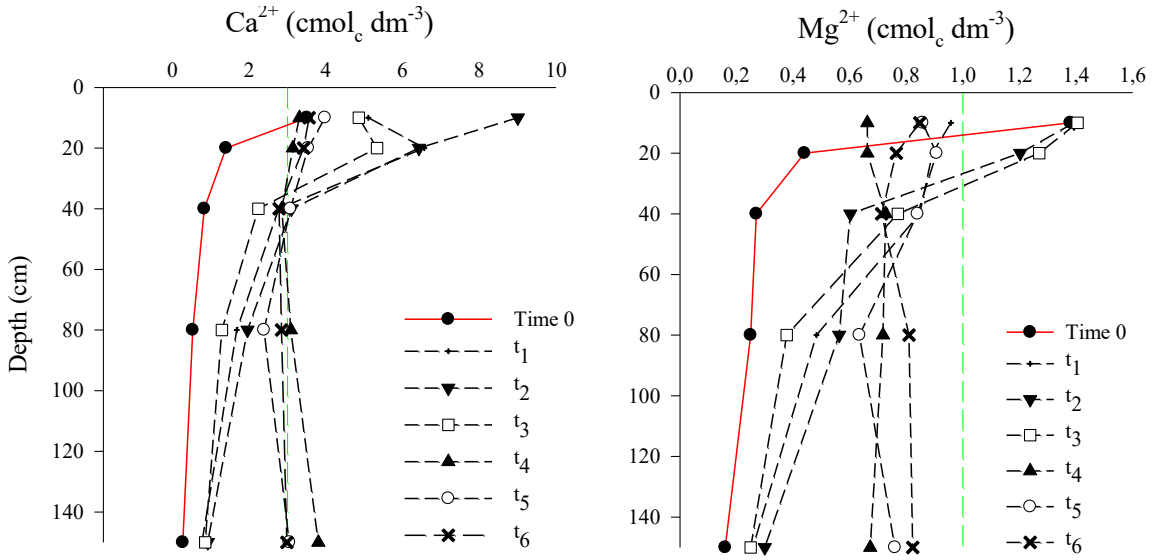


Figure 4. Ca^{2+} and Mg^{2+} contents in the different soil layers at time zero and after planting. The green line represents the critical level. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar.

The deep soil tillage treatments exhibited higher P levels in the subsurface layers compared to conventional tillage. As depth increased, P concentrations also increased, surpassing the critical threshold of 25 mg dm^{-3} in the soil. In contrast, in conventional tillage

treatments, P levels increased only in the surface layers, while no significant changes were observed in the subsurface. For K, an increase in levels was observed; however, the critical threshold of 100 mg dm³ was not reached. t_2 exhibited the highest levels throughout the profile, while in the subsurface, t_5 and t_6 matched the K levels of t_2 (Figure 5).

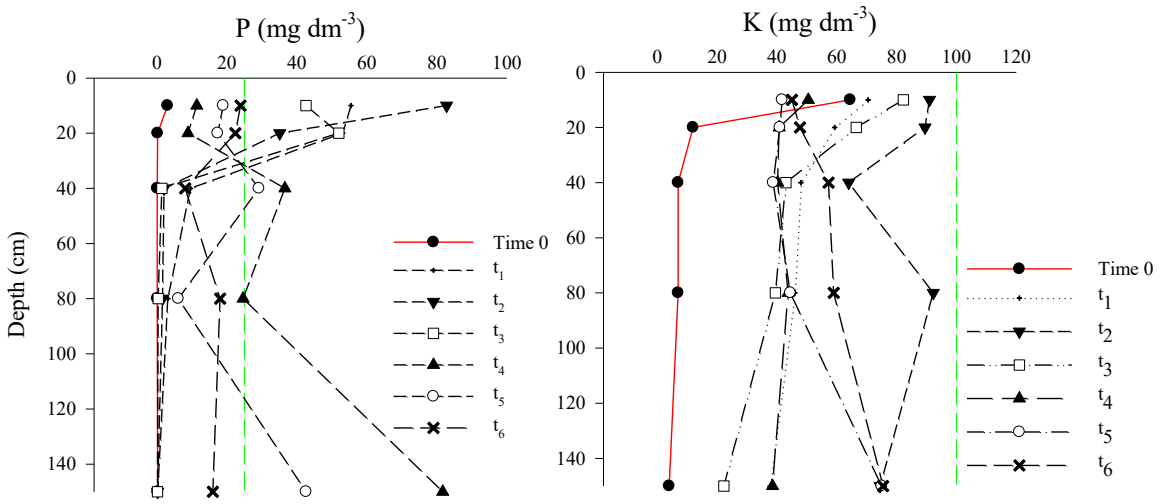


Figure 5. P and K contents in the different soil layers at time zero and after planting. The green line represents the critical lever. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar.

Soil management practices, including using fertilizers, soil acidity correctives, and organic matter inputs, promoted an increase in the potential cation exchange capacity (T) and base saturation of the soil (V). Results showed that the deep soil tillage treatments (t_4, t_6, and t_6) led to improvements in both the T at pH 7 and V, surpassing 60% (Figure 6), which is considered the ideal threshold for optimal crop development.

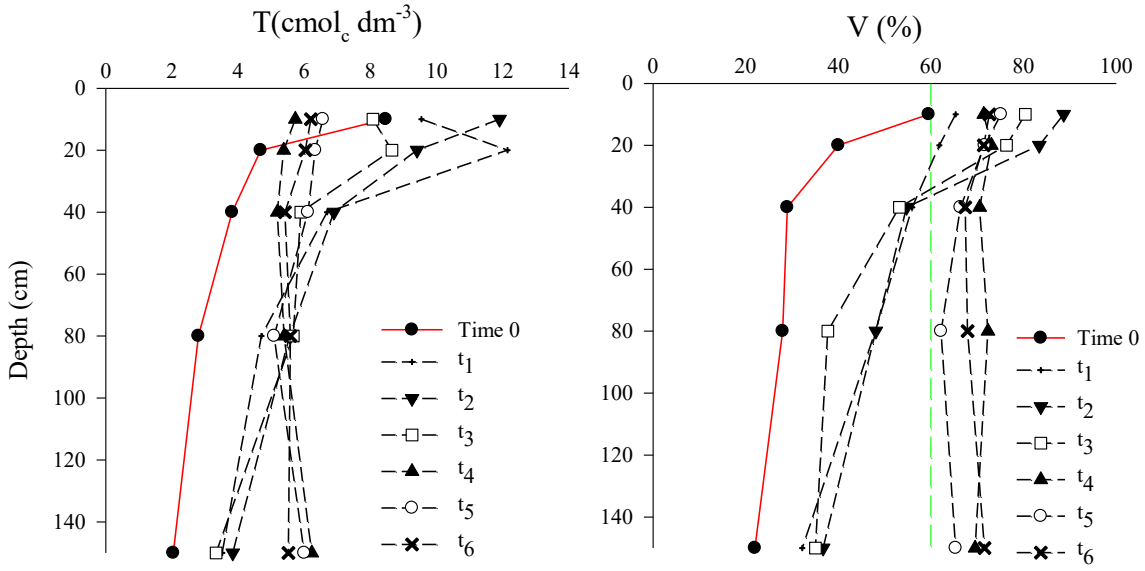


Figure 6. Cation exchange capacity at pH 7 (T) and base saturation (V) contents in the different soil layers at time zero and after planting. The green line represents the critical lever. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar.

A greater uniformity in nutrient levels was observed throughout the soil profile for the micronutrients B, Mn, Zn, and Fe. Generally, the conventional tillage treatments (t_1, t_2, and t_3) did not reach the critical levels of these micronutrients in the subsurface layers. In contrast, the deep tillage treatments (t_4, t_5, and t_6) showed adequate concentrations along the soil profile, successfully reaching the critical thresholds for these elements (Figure 7).

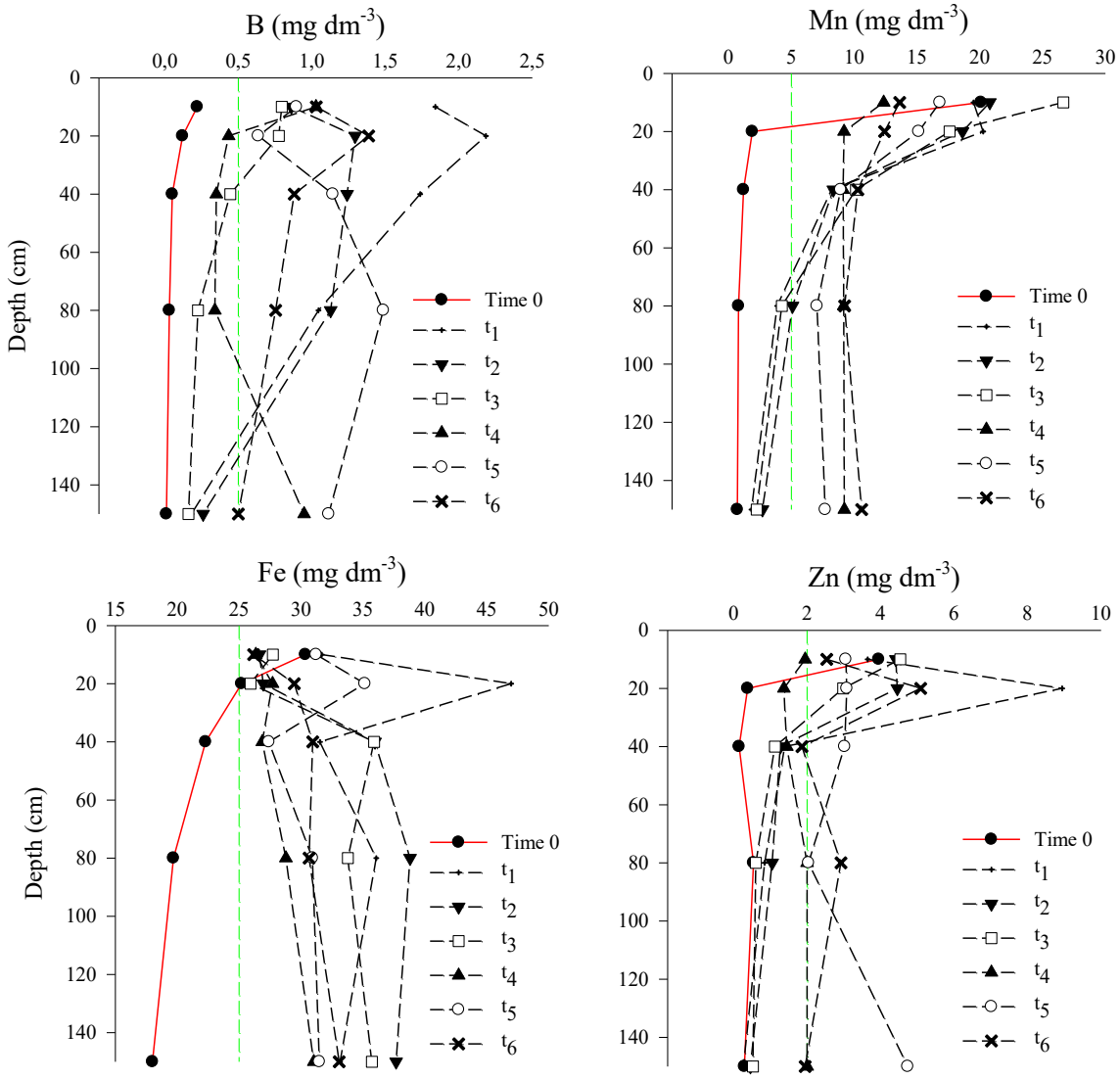


Figure 7. B, Mn, Zn and Fe contents in the different soil layers at time zero and after planting. The green line represents the critical lever. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar.

The incorporation of organic amendments, particularly when associated with deep soil tillage, as in t_5 and t_6, resulted in a significant increase in soil organic matter content throughout the entire soil profile (Figure 8). In contrast, t_2, which involved conventional tillage combined with organic inputs, showed increases in organic matter that were limited to the upper soil layers, up to approximately 40 cm depth. A similar pattern was observed for effective cation exchange capacity (t), where deep tillage treatments (t_4, t_5, and t_6) exhibited higher values

compared to pre-planting conditions, especially beyond the 40 cm depth. These increases were notably greater than those observed under conventional soil tillage treatments, suggesting enhanced chemical quality and nutrient retention capacity in deeper layers.

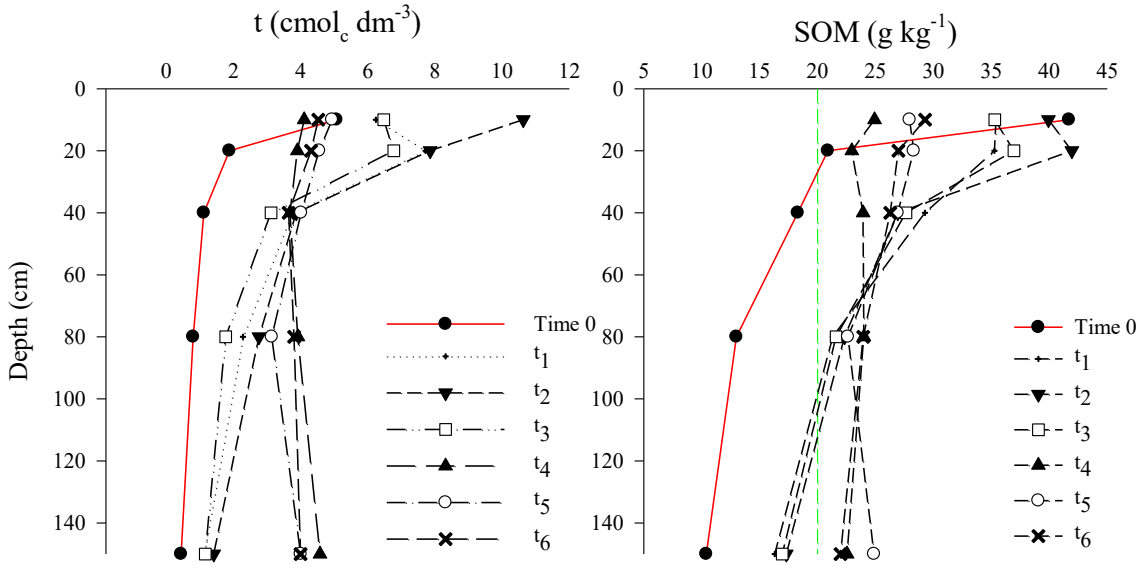


Figure 8. Effective cation exchange capacity (t) and soil organic matter (SOM) content in different soil layers at time zero and after planting. t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar.

4.2 Nutritional status of coffee plants

The application of the DRIS method for nutritional diagnosis. along with the evaluation of the BIK index (Table 5), generally indicated a K deficiency across all treatments, which is consistent with the results of the soil analysis (Table 4). Moreover, a similar nutritional pattern was observed across treatments, suggesting that plant growth and productivity were not negatively affected by inadequate nutrient management in any specific treatment. An exception was observed in the deep soil tillage treatments, which exhibited a nutritional imbalance related to Mn levels, indicating a possible underestimation of fertilization requirements under these soil management conditions. In the DRIS method, values below 1.5 were categorized as deficient, while values above 1.5 were considered excessive. The BIK delineates sufficiency

levels with an initial threshold of 83 % of the optimal level and an upper limit of 116 % of the optimal level (Fonseca et al., 2018).

Table 5. Nutritional diagnosis with Diagnosis and Recommendation Integrated System (DRIS) and Balanced Indexes of Kenworthy (BIK) methods of the coffee plants.

Treatment	Method	P	K	Ca	Mg	S	Cu	Fe	Zn	Mn	B
t_1	DRIS	-0.17	-1.83	0.57	0.23	0.48	-0.68	1.54	-1.59	-0.04	1.49
t_2		0.04	-1.58	0.84	0.11	0.67	-1.08	1.1	-1.51	-0.19	1.6
t_3		-0.11	-1.66	0.71	0.56	0.53	-0.64	1.37	-1.29	-0.99	1.51
t_4		0.45	-1.42	1.38	0.82	0.59	-1.63	1.3	-1.09	-1.86	1.46
t_5		0.35	-1.67	1.46	0.76	0.85	-1.17	0.79	-0.89	-1.84	1.37
t_6		0.34	-1.82	1.33	0.69	0.62	-1.2	1.01	-0.8	-1.66	1.49
t_1	BIK	89	59	108	99	107	77	126	81	93	136
t_2		88	58	106	89	103	68	110	80	88	131
t_3		85	58	104	102	101	74	118	81	81	130
t_4		96	61	118	105	99	62	113	82	76	123
t_5		95	58	122	104	108	67	104	83	77	122
t_6		97	57	121	105	104	67	110	84	77	130

Excessive
Above Normal
Normal
Below Normal
Deficient

4.3 The CO_2 concentration

The concentration of carbon dioxide in the soil (CO_2-C) exhibited a consistent increase with depth, peaking in the 60–150 cm soil layers (Figure 9). In the first year after planting (August 2019, winter period), the highest CO_2-C concentrations (µmol mol^{-1}) were observed in treatments involving deep soil tillage combined with organic amendments (t_5 and t_6), with significant differences across most soil depths (Figure 9A). No significant differences were detected in the 20–40 cm and 80–120 cm layers; however, at the surface layer (0–20 cm), treatments t_5 and t_6, incorporating cattle manure and biochar, showed significantly higher CO_2-C levels than the conventional tillage control (t_1). In the subsurface layers (particularly 120–

150 cm), treatments t_5 and t_6 reached CO_2-C concentrations of 8179 ppm, markedly higher than those recorded in the control (t_1 = 3764 ppm) and in t_2 (4747 ppm), both of which used conventional tillage practices.

In contrast, during the second sampling (February 2020, summer period), CO_2-C concentrations increased throughout the soil profile (Figure 9B), likely due to higher microbial activity stimulated by warmer temperatures and increased moisture availability. Treatments involving deep soil tillage and organic amendments (t_5 and t_6) again exhibited significantly higher CO_2-C levels than to conventional tillage treatments (t_1, t_2, and t_3). The maximum concentrations reached 11,549 ppm in t_5 and t_6, nearly double the average concentrations observed under conventional tillage (approximately 5580 ppm).

These findings highlight the enhanced biological activity and potential carbon turnover promoted by deep tillage and organic matter incorporation, particularly under favorable seasonal conditions.

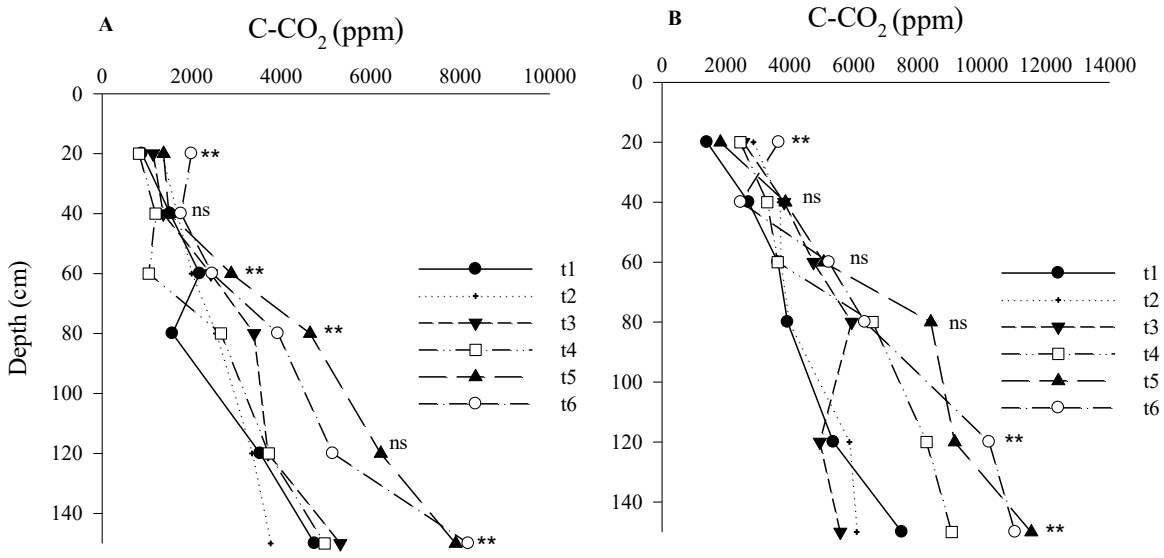


Figure 9. CO_2 concentration measured at six soil depths (0-20, 20-40, 40-60, 60-80, 80-120, and 120-150 cm) at two intervals after planting: one year (A) and two years (B). t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar. Asterisks indicate significant differences among treatments at each soil depth according to Tukey's test: ** $p < 0.05$.

4.4 Coffee quality

The sensory quality of coffee was closely associated with the distribution of fruit maturation stages at harvest (Table 6). Treatments involving deep soil tillage (150 cm) combined with organic amendments, particularly cattle manure and biochar (t_5 and t_6), under non-irrigated conditions resulted in higher cupping scores (82.38 and 82.17, respectively). Conversely, treatments with high percentages of green or overripe beans generally showed reduced sensory scores. For example, t_1 with irrigation, which had 67% overripe beans, yielded a lower score (79.50), while t_3, with 78.5% ripe beans, unexpectedly resulted in a moderate score (79.25), suggesting that factors beyond ripeness, such as specific nutrient combinations or possible post-harvest influences, may also affect final cupping score.

Under irrigated conditions, a lower proportion of ripe fruits was observed than non-irrigated ones. However, irrigation also reduced the occurrence of green fruits, contributing to cupping scores above 80 points in most treatments. The exception was treatment t_1, which recorded the lowest score (79.50), likely due to the high percentage of overripe fruits (67%), negatively impacting the sensory quality of the coffee.

Table 6. Fruit ripeness and cupping scores of coffee under non-irrigated and irrigated conditions.

ID	Irrigation	Treatments	Green	Ripe	Overripe	Cupping Score
			…….. % …….			
1		t_1	9.75	44.50	20.75	79.53
2		t_2	16.75	62.63	20.63	82.92
3	Non	t_3	13.75	78.50	7.75	79.80
4	irrigated	t_4	23.00	67.50	9.50	80.20
5		t_5	14.50	72.00	13.50	81.80
6		t_6	20.00	72.50	4.50	82.43
7		t_1	3.00	30.00	67.00	79.50
8		t_2	5.00	43.00	52.00	82.33
9	Irrigated	t_3	8.50	57.50	34.00	80.38
10		t_4	7.50	52.50	40.00	82.50
11		t_5	9.50	54.50	36.00	80.00

12	t_6	7.00	51.00	42.00	81.50

t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar.

4.5 Yield coffee

Over the five coffee harvests conducted between 2021 and 2025, the results showed statistically significant differences among treatments in most years, except for 2024, when no significant differences were detected ($p > 0.05$) (Table 7). Since no significant interaction was found between the factors "soil tillage system" and "irrigation" ($p > 0.05$), the mean values of the main factor (soil tillage treatments) were used for Tukey's pairwise comparison at a 5% probability level (Table 7).

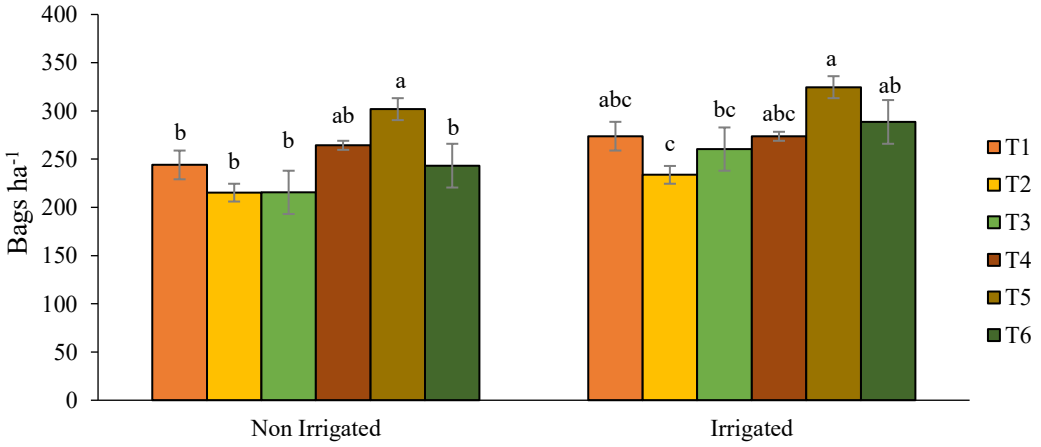
In the 2021 harvest, the treatments with conventional soil tillage (t_1, t_2, and t_3) exhibited significantly higher yields than those with deep tillage (t_4, t_5, and t_6). However, this trend was reversed in 2022 and 2023, where the deep tillage treatments demonstrated superior performance, especially t_5 and t_6, which consistently recorded higher yields.

In the 2025 harvest, significant differences were again observed. t_2 and t_4 recorded the lowest yields, suggesting a potential decline in the effectiveness of these management strategies in the later stages of the production cycle.

Cumulatively, after five harvests, Treatment t_5, which combined deep tillage at 150 cm depth, mineral fertilizer, and cattle manure, achieved the highest yield, averaging 313.23 bags ha^{-1}. This represents an increase of approximately 28 % compared to the lowest performing treatment, t_2, which yielded 224.49 bags ha^{-1} under conventional tillage with organic amendments (Figure 10). These findings underscore the potential of integrating deep tillage and organic amendments to enhance long-term coffee productivity. In addition, irrigation had a significant effect on yield per plant (L/plant), with higher values observed for irrigated plots of t_5 and t_2 when compared to their non-irrigated counterparts (Figure 10). This suggests that the combination of deep soil preparation, organic-mineral fertilization, and supplemental irrigation can synergistically improve coffee performance in water-limited environments.

Table 7. Historical coffee yields in bags ha^{-1} and L/plant

Treatment	2021		2022		2023		2024		2025		Cumulative	
						L/plant						
t_1	9.50	a	0.23	b	4.43	bc	7.70	a	4.28	ab	26.13	b
t_2	8.63	ab	0.36	b	3.75	c	7.08	a	3.42	b	23.23	bc
t_3	8.40	ab	0.16	b	4.78	bc	7.73	a	4.11	ab	25.18	bc
t_4	4.95	c	1.36	a	5.08	bc	6.90	a	3.33	b	21.62	c
t_5	6.73	bc	0.97	ab	7.95	a	8.80	a	6.53	a	30.98	a
t_6	6.68	bc	0.92	ab	5.93	b	8.45	a	3.58	ab	25.54	bc
						Bags ha^{-1}						
t_1	98,96	a	2.34	b	41.19	c	76.81	a	44.53	ab	258.89	bc
t_2	89.84	ab	3.78	b	37.96	c	74.24	a	35.59	b	224.49	c
t_3	87.50	ab	1.71	b	44.94	bc	76.10	a	42.84	ab	237.99	bc
t_4	51.56	c	14.17	a	51.08	bc	74.24	a	34.72	b	269.00	b
t_5	70.05	bc	10.08	ab	78.68	a	90.18	a	68.06	a	313.23	a
t_6	69.53	bc	9.57	ab	60.73	b	91.18	a	37.24	ab	265.91	b



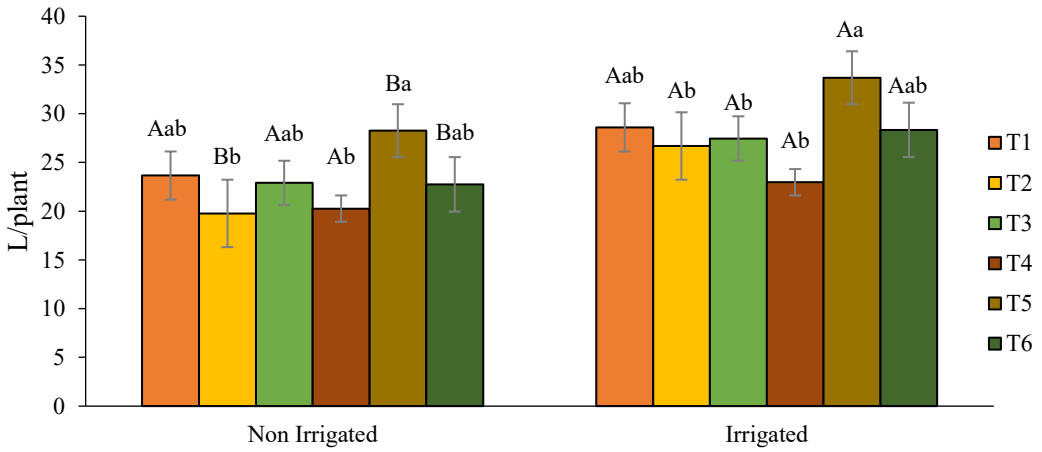


Figure 10. Cumulative yield in Bags ha^{-1} and L/plant as a function of soil tillage and fertilization with and without irrigation**.** t_1 = soil tillage at 60 cm depth and standard fertilization; t_2 = soil tillage at 60 cm depth, mineral fertilizer, cattle manure, and biochar; t_3 = soil tillage at 60 cm depth, standard fertilization, and gypsum amendment; t_4 = deep soil tillage at 150 cm depth and mineral fertilization; t_5 = deep soil tillage at 150 cm depth, mineral fertilizer, and cattle manure; t_6 = deep soil tillage at 150 cm depth, mineral fertilizer, cattle manure, and biochar. Means followed by the same lowercase letter within each irrigation condition do not differ significantly by Tukey's test at 5% significant. Uppercase letters denote significant differences between irrigation conditions for the same treatment.

5. DISCUSSION

Coffee productivity is influenced by a complex interplay of edaphoclimatic conditions and crop management practices. Among the most critical factors are the physical, chemical, and biological properties of the soil, as well as climatic variables and water availability during the crop's vegetative and reproductive stages (Silva et al., 2019; Partelli et al., 2013; Neto & Matsumoto, 2010). Given the sensitivity of coffee to these conditions, the adoption of integrated soil and water management strategies, such as correcting soil acidity, improving fertility, and applying irrigation, has become essential for achieving stable and high yields (Scalco et al., 2011; Vicente et al., 2017).

The findings of this study reinforce the importance of such integrated approaches. Treatments involving deep soil tillage, especially when combined with organic amendments, resulted in notable improvements in soil conditions and plant performance. These practices not only enhanced the physical structure of the soil but also increased its fertility throughout the profile. This aligns with the results of Calvache et al. (2025), who observed significant increases in nutrient concentrations to depths of up to 150 cm, contributing to improved coffee productivity when compared to conventional tillage systems. In addition, the development of a deeper and more favorable soil profile likely facilitated greater root growth and distribution, thereby improving the plant's access to water and nutrients, factors directly linked to enhanced physiological responses and yield potential (Zhang et al., 2020).

The P and K are essential macronutrients for plant growth, playing vital roles in multiple physiological and metabolic processes. Phosphorus is closely associated with energy transfer, root development, and reproductive functions, while K is critical for osmoregulation, enzyme activation, photosynthesis, and the transport of assimilates within the plant (Wang et al., 2013; Khan et al., 2023). Adequate availability of both nutrients is therefore fundamental for sustaining the growth and productivity of coffee plants throughout their phenological stages. In this study, treatments involving deep soil tillage (t_4, t_5, and t_6) exhibited higher P concentrations throughout the soil profile, with particularly marked increases beyond the 80 cm depth compared to conventional tillage treatments. These treatments succeeded in reaching or exceeding the critical threshold for P, indicating improved vertical distribution and availability of this nutrient. A similar trend was observed for K; however, despite the elevated levels in deep-tilled treatments, the concentrations did not reach the critical sufficiency range. These outcomes are consistent with the findings of Calvache et al. (2025) and Alves et al. (2022), who

reported increased subsoil concentrations of both P and K under deep tillage, underscoring the technique's potential to enhance nutrient availability in deeper soil horizons.

Favorable outcomes were observed in response to the use of deep soil tillage combined with efficient corrective amendments, particularly in terms of increased pH and reduced the H+Al. These practices promoted significant improvements in the chemical attributes of the soil, especially within subsurface layers. Although the initial pH values were already within the recommended range for coffee cultivation (5.5 – 6.5) as proposed by Corrêa et al. (2001), marked increases in pH were recorded at greater depths, reaching up to 6.33 at 150 cm. These findings underscore the capacity of deep tillage to facilitate the vertical redistribution of corrective amendments, thereby enabling the amelioration of soil acidity beyond the layers typically influenced by conventional surface applications. Treatments involving deep tillage (t_4, t_5, and t_6) also exhibited a pronounced reduction in potential acidity along the soil profile, particularly in t_5 and t_6. This decline in H+Al levels is consistent with the observed rise in pH and highlights the effectiveness of these practices in neutralizing exchangeable acidity. Similar outcomes have been reported by Campos et al. (2022), who demonstrated that deep incorporation of lime contributes to the enhancement of subsoil chemical conditions, favoring root growth and the establishment of more resilient cropping systems.

Additionally, an increase in the availability of Ca^{2+} and Mg^{2+} was observed in deep tillage treatments compared to conventional systems (t_1, t_2, and t_3), indicating improved nutrient stratification and redistribution across the soil profile. For Ca^{2+}, critical levels were reached even in deeper layers under deep tillage, suggesting higher mobility and availability resulting from more effective incorporation of dolomitic lime. A similar trend was observed for Mg^{2+}, particularly in treatments t_4, t_5, and t_6, which exhibited elevated concentrations in the subsurface. However, Mg^{2+} levels remained below the critical threshold in some layers, pointing to a possible limitation in its supply. This outcome may reflect an underestimation of lime application rates in deep tillage systems, given the substantially larger soil volume affected. As highlighted by Moreira et al. (2025), dolomitic lime serves not only as a neutralizing agent of acidity but also as a primary source of Ca^{2+} and Mg^{2+}. Nevertheless, when used in systems involving intensive soil mobilization, such as deep tillage, lime requirements must be adjusted accordingly to ensure uniform correction throughout the profile. This concern was also addressed by Shang et al. (2024), who emphasized the importance of aligning the dosage of corrective inputs with the effective soil volume to optimize nutrient availability and maintain chemical balance in deeper horizons.

Base saturation is a key indicator of soil fertility, reflecting the proportion of exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) relative to the soil's cation exchange capacity at pH 7.0 (Novais et al., 2007). In this study, treatments involving deep soil tillage exhibited a superior capacity to build and sustain soil fertility compared to conventional tillage systems, resulting in base saturation values exceeding 60%, a threshold considered optimal for high-yielding coffee cultivation (Guarçoni, 2017). This improvement was further enhanced by incorporating organic amendments, particularly cattle manure and biochar, which significantly increased base saturation along the soil profile in treatments t_4, t_5, and t_6. The positive effect of these amendments can be attributed not only to their direct contribution of exchangeable bases but also to their role in improving soil structure and buffering capacity. These findings are corroborated by parallel increases in the soil's effective cation exchange capacity, which also presented higher values under deep tillage treatments. The observed enhancement in cation exchange capacity is closely associated with the increase in SOM content promoted by the addition of organic residues. As reported by Conceição et al. (2005), higher SOM levels contribute to greater surface area and functional groups available for cation adsorption, thereby improving the soil's ability to retain and supply nutrients.

Taken together, these results underscore the synergistic benefits of deep soil tillage and organic amendments in enhancing the chemical fertility of deeper soil layers. Such practices not only support better nutrient retention and distribution but also contribute to improved nutrient use efficiency, ultimately creating more favorable conditions for root growth and crop productivity (Besen et al., 2021; Cai et al., 2014).

The greater uniformity and adequacy in the concentrations of B, Mn, Zn, and Fe under deep tillage treatments (t_4, t_5, and t_6), compared to conventional tillage systems (t_1, t_2, and t_3), underscore the effectiveness of deep soil management in enhancing micronutrient availability throughout the soil profile. This improvement can be attributed to enhanced soil structure and increased root exploration capacity, which collectively promote the mobilization and uptake of nutrients from subsurface layers (Khan et al., 2018) Moreover, the incorporation of organic amendments, such as cattle manure and biochar in treatments t_5 and t_6, likely contributed to the improved micronutrient status by increasing cation exchange capacity, enhancing soil buffering capacity, and stimulating microbial activity, all of which are critical for micronutrient solubility and stability (Lehmann et al., 2011; Alkharabsheh et al., 2021). Achieving adequate micronutrient concentrations at greater depths is essential for maintaining balanced plant nutrition and preventing deficiencies that can compromise physiological processes, growth, and crop quality, particularly under limited water availability, when deep

root uptake becomes more significant (Silva et al., 2021; Dubberstein et al., 2019). Thus, the integration of deep tillage with organic inputs emerges as a promising agronomic strategy to enhance micronutrient dynamics, sustain crop productivity, and improve the resilience of coffee production systems under edaphoclimatic constraints.

The CO_2-C concentrations measured during both sampling periods, winter and summer, revealed consistently higher values in treatments involving deep soil tillage, particularly in t_5 and t_6. These results suggest that deep tillage, when combined with organic amendments such as cattle manure and biochar, can enhance biological activity and root development across the soil profile, especially in deeper layers that are typically less biologically active under conventional management. The increased root biomass and exudation, in combination with elevated microbial activity stimulated by the organic inputs, likely contributed to greater CO_2-C production through enhanced soil respiration (Wen et al., 2022; Lal, 2016). Cattle manure provides a readily available source of labile carbon and nutrients, promoting microbial proliferation, while biochar is known to improve soil aeration and moisture retention, offering a favorable environment for microbial colonization and sustained activity (Lehmann et al., 2011; Shyam et al., 2025). Deep tillage may also facilitate deeper root penetration, leading to greater rhizodeposition and microbial stimulation at depth (Yu et al., 2019). These interactions collectively enhance microbial-driven carbon turnover, as supported by Kim et al. (2020), who reported significant shifts in microbial structure and function in response to changes in soil management practices.

Furthermore, elevated CO_2-C concentrations in summer compared to winter indicate a strong seasonal influence, with higher temperatures and moisture availability promoting microbial and root respiration. This seasonal dynamic underscore the sensitivity of CO_2 fluxes to climatic factors and soil biological activity (Contosta et al., 2011).

The sensory quality of *Coffea arabica* was closely linked to the uniformity of fruit ripening at harvest (Haile and Kang, 2020). Treatments involving deep soil tillage combined with organic amendments, especially cattle manure and biochar, under non-irrigated conditions led to superior cup quality due to a higher proportion of ripe cherries and fewer immature or overripe fruits. However, even with high ripe fruit percentages, sensory quality was not guaranteed, suggesting that other factors like nutrient status, plant stress, and post-harvest handling also play critical roles (Velásquez et al., 2019). Irrigation alone did not ensure better quality, highlighting the importance of integrated soil and crop management practices to promote uniform maturation and enhance beverage quality (Mintesnot et al., 2015; DaMatta et al., 2007).

On the other hand, the productivity results indicated that deep soil tillage had a positive impact on coffee yield, with an increase of approximately 27 % compared to treatments under conventional tillage systems. This improvement was further influenced by the irrigation strategy, which consistently affected plant productivity (L plant^{-1}) over the five harvest seasons evaluated. The enhanced productivity observed under deep tillage can be attributed to multiple interrelated factors, including improved soil physical structure, greater nutrient availability in deeper layers, and enhanced root growth and functionality (Silva et al., 2021). These conditions favor more efficient water and nutrient uptake, especially under stress conditions such as drought, thus sustaining plant development and yield potential over time. These findings are in line with previous studies that highlight the beneficial effects of deep soil tillage on crop performance, particularly in perennial systems like coffee (Calvache et al., 2025).

6. CONCLUSION

This study demonstrated that the integration of deep soil tillage and organic amendments, particularly cattle manure and biochar, significantly improved the chemical fertility of the soil profile, enhanced biological activity (as evidenced by increased CO_2-C concentrations), and positively influenced both the productivity and sensory quality of *Coffea arabica*. Deep tillage practices promoted greater nutrient availability, root development, and base saturation at depth, even under non-irrigated conditions, contributing to more resilient and productive coffee systems.

Although irrigation positively affected fruit production volume, as reflected in higher yield per plant (L/plant) in irrigated treatments, particularly under deep tillage with organic amendments, this increase was not reflected in significant gains in processed coffee yield (bags ha^{-1}). This suggests that irrigation influenced the harvest volume, but not the final conversion efficiency to marketable beans, possibly due to differences in fruit ripeness, water content, or processing losses. Consequently, no significant differences in bags ha^{-1} were observed between irrigation regimes, indicating that irrigation had a greater effect on gross yield than on net productivity.

These findings underscore the agronomic potential of combining physical and organic soil management strategies to sustainably increase yield and quality in coffee production. Future research should explore the long-term effects of these practices on soil health, carbon dynamics, and climate resilience in coffee agroecosystems.

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Chapter 3 Nutrient export in different cultivars of *Coffea arabica l.* grown in the Cerrado Mineiro

1. ABSTRACT

The Cerrado Mineiro region is one of the most significant coffee-producing areas in Brazil, renowned for the exceptional quality of its beans. Different varieties of *Coffea arabica* L. have been used by growers, but specific information on their adaptation to edaphoclimatic conditions, quality, and nutrient export remains limited. This study aimed to quantify nutrient export in the fruit of *Coffea arabica* cultivars in the Cerrado Mineiro region. The yield and cup quality of twenty-four coffee varieties were evaluated over two harvests in eight locations. Representative fruit samples were collected in triplicate, air-dried, and then separated into coffee beans and husks for macro and micronutrient analysis. The macronutrient export in the fruit followed the order: K > N > Ca > S > P > Mg. For micronutrients, the export order was Fe > Zn > Mn > Cu > B. On average, the coffee bean contained most of the N (62%), P (60%), Mg (71%), S (55%), Mn (54%), Zn (53%), and Cu (53%), whereas the husk contained 56% of K, 70% of Ca, 71% of Fe, and 84% of B exported in the fruit. Nutrient export in the fruit did not show statistically significant differences among coffee varieties, except for Fe and B. The varieties IBC 12 19F/6, Catuaí Vermelho IAC 99, and Acauã 365 exhibited higher Fe export, while Catuaí Amarelo L2SL, IPR 103, Catuaí Amarelo 32, Rouxinol, and Catuaí Vermelho IAC 99 showed higher B export. Linear regression models were fitted to estimate the nutritional demand of coffee fruits based on yield, providing essential insights for nutritional management adjustments in coffee production in the Cerrado Mineiro region.

Keywords: Coffee plant, extraction, husk, bean, nutritional management.

2. INTRODUCTION

The Cerrado Mineiro region is one of the most important areas for coffee production in Brazil and is widely recognized internationally for the exceptional quality of its beans (Conab, 2023). In this region, *Coffea arabica* L. is the predominant species cultivated, with a wide diversity of cultivars adapted to various soil and climatic conditions. The agronomic characterization of these cultivars, along with the analysis of nutrient export, is essential for optimizing both yield and coffee quality, as well as contributing to the sustainability of agricultural practices (Fernandes et al., 2020).

During the development of coffee fruits, there are significant variations in both the concentration and quantity of accumulated nutrients, as well as in dry matter production. According to Moraes and Catani (1964), nutrient uptake and dry matter accumulation increase substantially from the fourth month after flowering. Matiello et al. (2005) emphasize that nutrient demand is relatively low during the flowering and pinhead stages but increases significantly as the fruits progress to the grain-filling (green-solid) and ripening stages. According to Cannell (1994), in the final growth stages, the fruits accumulate up to 95% of the potassium, phosphorus, and nitrogen. During the final stage, as ripening occurs, the pericarp increases in size, accumulates fresh and dry mass, and the fruits change color, ranging from red to yellow, depending on the cultivar (DaMatta et al., 2007).

The export of nutrients by coffee fruits is a determining factor in the adequate replenishment of soil nutrients, directly influencing fertilization recommendations. Studies indicate that nutrient extraction by fruits follows a decreasing order: K > N > Ca > Mg > S > P > Mn > B > Cu > Zn, with potassium being the most exported nutrient (Chaves, 1982). Additionally, research shows that in the two months prior to full ripening, the fruits accumulate approximately 49% of the nitrogen, 36% of the phosphorus, and 39% of the potassium relative to the total amounts present at maturity (Moraes & Catani, 1964).

Nutrient export by the fruits provides valuable information to guide field fertilization. Replacing the nutrients exported by the fruits is the recommended approach in fertile soils, ensuring the sustainability of production over the years. Nutrient export by fruits is a fundamental component in the development of nutritional recommendation models, such as the one developed by Prezotti (2001), known as "FERTICALC Café Arábica", which was later renamed "FERTI-UFV Café Arábica". These models offer the advantage of being dynamic, allowing adjustments based on continuously updated data on nutrient removal by crops. Accurate and up-to-date data are essential for improving the precision of

recommendations, as they reflect the actual needs of plants under modern agricultural conditions (Prezotti, 2001; Oliveira et al., 2005; Santos et al., 2008; Tittonel et al., 2008).

In this context, evaluating nutrient export in *Coffea arabica* fruits among different cultivars is crucial for nutritional balancing, allowing fertilization to be aligned with the specific demands of current varieties. Therefore, studies covering a broader range of cultivars can enhance the accuracy of fertilization recommendations and soil fertility management. The objective of this study was to quantify nutrient export by the fruits of *Coffea arabica* cultivars in the Cerrado Mineiro region.

3. MATERIAL AND METHODS

3.1 Experimental arrangement

The experimental area is located in the region of Carmo do Paranaíba, Minas Gerais, Brazil, across eight farms (Figure 1). The climate is classified as Aw according to Köppen (1948), characterized as tropical with a dry winter. The region has a rainy season during the summer (from November to April) and a well-defined dry season in the winter (from May to October), with July being the driest month. The average temperature in the coldest month is above 18°C, and the annual precipitation ranges from 750 mm to 1800 mm.

In this area, twenty-four *Coffea arabica* L. cultivars were planted in 2016, using a 3.8 × 0.5 m spacing. The soil is classified as Red-Yellow Latosol (LVa) according to the Brazilian Soil Classification System (IBGE, 2007). Prior characterization of the cultivars, including information on their origin, disease resistance, vigor, branching pattern, climatic adaptation, maturation cycle, and plant size, was based on data from previous studies (Carvalho et al., 2022) (Table S1).

Coffee yield was assessed over the years by harvesting three plants from the useful plot area. The yield (L $plant^{-1}$) was converted into 60 kg bags per hectare (bags ha^{-1}), considering the specific processing yield of each cultivar.

Beverage quality was evaluated for the harvest seasons from 2019 to 2023. Sensory analysis was performed by a certified cupper accredited by the Brazil Specialty Coffee Association (BSCA, 2024) and holder of the Q Grader certification.

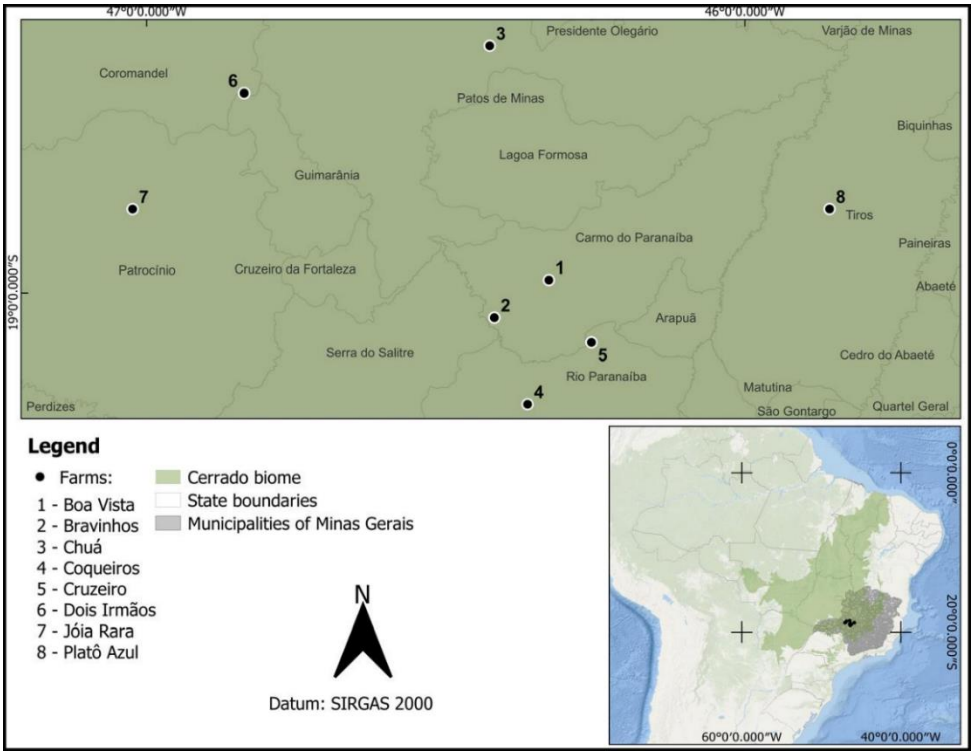

Figure 1. Mapping of the experimental area in the region of Carmo do Paranaíba, conducted by the Coffee Growers Association of the Carmo do Paranaíba Region (ASSOCAFÉ) across eight farms.

3.2 Nutrient export in the fruit

In 2023 (six years after planting), ripe fruits were harvested in triplicate to assess nutrient export. The fruits were separated into beans and husks and dried in a forced-air oven at 65°C until constant weight. Subsequently, the material was ground and subjected to total digestion using a mixture of nitric and perchloric acids in a 3:1 ratio to determine macro- and micronutrient contents by inductively coupled plasma optical emission spectrometry (ICP-OES), following the methodology described by do Carmo et al. (2000). For nitrogen determination, the material was digested with sulfuric acid and quantified using the Kjeldahl method (1883).

The total export of macro- and micronutrients in the coffee fruit was determined, as well as the percentage distribution between the husk and the bean.

Equation 1:

$$\%\ Nutrient = \frac{Content\ in\ husk\ or\ bean * 100}{Total\ content\ in\ the\ fruit}$$

Nutrient export by the fruits, expressed per 60-kg coffee bag, was calculated using the following equation:

Equation 2:

$$y(\ kg\ bag^{-1}) = \frac{Extracted\ content\ in\ g\ kg^{-1}\ \times 60}{1000}$$

3.3 Statical analysis

Productivity data were statistically analyzed using Tukey's test at a 5% significance level, considering each demonstration plot as a replicate. To evaluate nutrient export in the fruits of each cultivar, specific regression models were generated for each nutrient as a function of yield. The significance of the models was tested using the F-test, and the regression coefficients were evaluated using the t-test, both at a 1% significance level, using the SPEED Stat software (Carvalho et al., 2020). In addition, the nutrient exportation data were subjected to statistical analysis using the Scott–Knott clustering test at a 10% probability level to group cultivars according to their performance.

4. RESULTS

The average yield values evaluated across eight farms were generally similar, averaging 38 bags ha^{-1}, except for the cultivar MGS Paraíso 4, which showed a lower average yield of 28.65 bags ha^{-1}, and the cultivar IPR 107, which reached a higher average of 61.79 bags ha^{-1}. It is worth noting that IPR 107 was evaluated in only three farms (Table 1).

The sensory quality assessment of coffee showed scores ranging from 82.47 to 84.80, with an average of 83.1 points (Table 1). In general, no significant score discrepancies were observed among the evaluated cultivars, and scores above 80 indicate that all 24 cultivars have potential for specialty coffee production in the Cerrado region (BSCA, 2024).

Analysis of nutrient export in coffee fruits and its partitioning between the bean and the husk revealed slight variation among the cultivars (Table 2). The nutrient export data showed that 56 % of K and 70 % of Ca were concentrated in the coffee husk (Table 2), along with more than 50 % of each micronutrient (Table 3). In contrast, the bean exported the majority of N, P, and Mg, with 62 %, 60 %, and 70 %, respectively (Table 2). These findings are fundamental for nutrient balance planning in the system and highlight the importance of returning coffee husks to the field as a means of recycling appreciable amounts of nutrients, especially Ca, K, and micronutrients.

In general, the decreasing order of macronutrients in the coffee bean was: N > K > Mg > S > P > Ca. However, cultivars such as Arara, Bourbon Amarelo J9, Catuaí Vermelho IAC 99, Catucaí Amarelo L2SL, Catucaí Vermelho (Guará), IBC 12 19 F/6, MGS Aranãs, MGS Paraíso 4, Rouxinol, and Topázio MG 1190 showed higher P content than S. Regarding micronutrient export in the coffee bean, the observed decreasing order was: Fe > Mn > Cu > Zn > B (Table 3). On the other hand, nutrient export in the coffee husk followed the decreasing order of K > N > Ca > S > P > Mg for macronutrients, and Fe > Mn > Cu > B > Zn for micronutrients.

The amounts of macro- and micronutrients exported in the bean and husk, expressed per 60-kg bag of processed coffee, are presented in Tables 4 and 5, respectively. Based on these results, a multiplication factor (Fm) was established to estimate nutrient export at different yield levels. Furthermore, it was possible to quantify the total nutrient export and the respective proportion allocated to beans and husks as a function of yield (Table 7). Accordingly, fertilization planning can be based on replenishing nutrients exported by the fruits, allowing for more efficient nutrient management. The regression models generated enable estimation of the

crop's nutritional demand according to expected yield, assisting in fertilizer recommendation (Table 6).

The results indicate that a single linear model can be used to estimate nutrient export for the 24 cultivars grown in the Cerrado region (Table 6), except for B and Fe, which showed distinct behavior across at least four groups of cultivars (Figures 2 and 3). On average, the model estimates the export of the following nutrient amounts per 60-kg processed bag of coffee: macronutrients (kg) – N: 2.0, P: 0.23, K: 2.08, Ca: 0.21, Mg: 0.15, S: 0.4; and micronutrients (g) – Zn: 0.69, Cu: 1.61, Mn: 2.55, Fe: 3.34.

For B, the most efficient cultivars in nutrient use belong to Group 1 (IAC 125 RN, Asabranca, Acauã 365, Acauã Novo, Arara, IPR 107, Acauã CV8), with lower B export, averaging 0.8 g per 60-kg processed bag. Group 2 (Catucai Amarelo L 24/137; Sarchimor MG 8840; IBC 12 19F/6; MGS Paraiso 4; IPR 100; Catiguá MG2; MGS Paraiso 2; MGS Paraiso 3; Topazio MG 1190; MGS Aranãs; Catucai Vermelho (guará); Bourbon Amarelo J9; Catucaí Amarelo L2SL, IPR 103, Catuaí Amarelo 32, Rouxinol, and Catuaí Vermelho IAC 99) includes the least efficient cultivars, exporting up to 1.97 g per bag. (Figure 2).

Regarding Fe, the statistical analysis using the Scott–Knott test at a 10% probability level indicated no significant differences in nutrient export among cultivars. Therefore, Fe was the only nutrient for which no adjustment was performed, and it was not considered in the fertilization recommendation plan. On average, cultivars exported approximately 6.5 g of Fe per 60-kg processed bag

Table 1. Average yield and cup quality of coffee cultivars (*Coffea arabica*) evaluated on eight farms in the Cerrado Mineiro region

Cultivar	Average Yield [(1)]		Cup Quality
Acauã CV8	44,26	ab	82,88
Acauã Lav. 14-10	43,78	ab	83,85
Acauã Novo	42,94	ab	82,82
Arara	44,78	ab	84,80
Asabranca Lav. 14-5	40,43	ab	82,91
Bourbon Amarelo IAC J9	40,77	ab	83,63
Catiguá MG2	39,52	ab	83,95
Catuaí Amarelo IAC 32	45,20	ab	83,03
Catuaí vermelho IAC 99	42,56	ab	83,00

Catucaí Amarelo 24/137	51,31	a	83,23
Catucaí Amarelo 2SL SSP	45,98	ab	83,38
Guará	50,30	a	83,79
IAC 125 RN	44,70	ab	83,04
IBC 12 19F/6	45,95	ab	82,86
IPR 100	52,33	a	82,47
IPR 103	47,94	a	82,72
IPR 107	60,61(2)		83,26
MGS Aranãs	44,40	ab	83,07
MGS Paraíso 2	42,46	ab	84,25
MGS Paraíso 3	46,54	ab	83,48
MGS Paraíso 4	33,68	b	83,50
Rouxinol	47,18	a	83,16
Sarchimor MG 8840	43,71	ab	82,78
Topázio MG 1190	39,81	ab	83,20

(1) Average yield (bags per hectare) from eight demonstration plots (vitrines) on different farms in the Cerrado Mineiro region, including irrigated and non-irrigated areas

(2) Yield based on only three farms.

Table 2. Macronutrient export and percentage distribution between husk and bean in different coffee cultivars (*Coffea arabica*).

Cultivar	N			P			K			Ca			Mg			S		
	Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean
	g kg^{-1}	%		g kg^{-1}	%		g kg^{-1}	%		g kg^{-1}	%		g kg^{-1}	%		g kg^{-1}	%	
Acauã 365	33,5	38,1	61,9	2,0	38,9	61,1	36,1	55,2	44,8	3,2	71,2	28,8	2,6	27,4	72,6	2,3	44,1	55,9
Acauã CV8	33,6	38,6	61,4	2,1	43,0	57,0	34,9	52,1	47,9	3,6	67,2	32,8	2,6	26,4	73,6	2,4	45,0	55,0
Acauã Novo	33,5	37,6	62,4	2,0	34,2	65,8	37,6	54,1	45,9	3,4	70,0	30,0	2,6	29,4	70,6	2,4	43,4	56,6
Arara	33,8	37,3	62,7	2,0	33,5	66,5	33,5	55,2	44,8	3,6	69,4	30,6	2,4	26,9	73,1	2,3	44,4	55,6
Asabranca	34,1	38,0	62,0	1,8	42,7	57,3	33,7	55,1	44,9	3,3	66,1	33,9	2,3	30,4	69,6	2,1	46,2	53,8
Bourbon Amarelo J9	34,2	38,2	61,8	2,3	33,7	66,3	36,1	59,6	40,4	3,9	68,7	31,3	2,7	28,1	71,9	2,5	46,3	53,7
Catiguá MG2	33,1	37,9	62,1	2,1	39,2	60,8	32,7	50,6	49,4	3,3	70,1	29,9	2,7	29,5	70,5	2,3	43,3	56,7
Catuai Amarelo 32	33,7	38,3	61,7	2,2	41,1	58,9	33,6	54,6	45,4	3,9	67,6	32,4	2,5	31,9	68,1	2,5	46,1	53,9
Catuaí Vermelho IAC 99	33,3	37,3	62,7	2,3	43,0	57,0	36,0	57,5	42,5	3,7	73,8	26,2	2,6	31,4	68,6	2,5	48,4	51,6
Catucaí Amarelo L 24/137	33,3	37,1	62,9	1,9	37,2	62,8	34,9	63,3	36,7	3,4	68,1	31,9	2,3	28,4	71,6	2,3	44,3	55,7
Catucaí Amarelo L2SL	33,7	37,3	62,7	2,3	41,9	58,1	34,1	58,9	41,1	3,6	69,7	30,3	2,4	29,7	70,3	2,4	44,9	55,1
Catucaí Vermelho (Guará)	33,1	37,4	62,6	2,3	41,6	58,4	34,0	56,2	43,8	3,0	68,3	31,7	2,7	29,7	70,3	2,4	46,7	53,3
IAC 125 RN	33,2	37,6	62,4	2,0	35,6	64,4	34,4	56,5	43,5	3,1	59,9	40,1	2,5	26,6	73,4	2,2	43,5	56,5
IBC 12 19F/6	33,5	37,8	62,2	2,3	43,3	56,7	35,4	60,6	39,4	3,6	71,5	28,5	2,5	31,1	68,9	2,4	49,3	50,7
IPR 100	33,5	38,1	61,9	2,1	40,1	59,9	31,7	53,9	46,1	3,3	68,3	31,7	2,3	27,4	72,6	2,3	44,3	55,7
IPR 103	33,5	37,8	62,2	2,2	43,2	56,8	35,9	56,4	43,6	3,8	72,6	27,4	2,5	29,8	70,2	2,5	46,1	53,9
IPR 107	33,2	37,9	62,1	2,2	37,7	62,3	35,8	53,1	46,9	3,3	69,8	30,2	2,5	24,5	75,5	2,5	42,8	57,2
MGS Aranãs	32,9	37,8	62,2	2,3	39,5	60,5	35,6	55,2	44,8	3,6	73,2	26,8	2,7	26,8	73,2	2,5	46,4	53,6

MGS Paraíso 2	33,1	38,5	61,5	2,1	39,4	60,6	34,2	54,6	45,4	3,2	69,8	30,2	2,5	27,3	72,7	2,3	41,8	58,2
MGS Paraíso 3	33,9	39,0	61,0	2,4	47,2	52,8	33,7	56,0	44,0	3,4	67,1	32,9	2,7	28,9	71,1	2,4	45,5	54,5
MGS Paraíso 4	33,5	38,0	62,0	2,1	38,5	61,5	33,5	57,3	42,7	3,6	67,8	32,2	2,6	29,7	70,3	2,4	45,7	54,3
Rouxinol	34,4	38,2	61,8	2,2	41,4	58,6	34,8	58,0	42,0	3,4	72,4	27,6	2,5	27,4	72,6	2,4	47,4	52,6
Sarchimor MG 8840	33,2	38,4	61,6	2,0	36,0	64,0	33,4	54,1	45,9	3,7	75,0	25,0	2,5	28,2	71,8	2,3	43,2	56,8
Topazio MG 1190	33,5	37,6	62,4	2,1	43,9	56,1	34,5	57,0	43,0	3,4	73,8	26,2	2,4	29,5	70,5	2,3	49,5	50,5
Mínimum	32,9	37,1	61,0	1,8	33,5	52,8	31,7	50,6	36,7	3,0	59,9	25,0	2,3	24,5	68,1	2,1	41,8	50,5
Maximum	34,4	39,0	62,9	2,4	47,2	66,5	37,6	63,3	49,4	3,9	75,0	40,1	2,7	31,9	75,5	2,5	49,5	58,2
Average	33,5	37,9	62,1	2,1	39,8	60,2	34,6	56,0	44,0	3,5	69,6	30,4	2,5	28,6	71,4	2,3	45,4	54,6

Table 3. Micronutrient export and percentage distribution between husk and bean in different coffee cultivars (*Coffea arabica*).

Cultivar	**Fe**			**B**			**Zn**			**Cu**			**Mn**		
	Export	**Husk**	**Bean**	**Export**	**Husk**	**Bean**	**Export**	**Husk**	**Bean**	**Export**	**Husk**	**Bean**	**Export**	**Husk**	**Bean**
	mg kg^{-1}	**%**		mg kg^{-1}	**%**		mg kg^{-1}	**%**		mg kg^{-1}	**%**		mg kg^{-1}	**%**	
Acauã 365	162,3	83,2	16,8	13,9	76,3	23,7	50,3	50,3	49,7	27,7	57,1	42,9	43,2	49,2	50,8
Acauã CV8	90,7	72,4	27,6	15,9	79,3	20,7	47,0	47,0	53,0	26,4	54,6	45,4	47,9	54,5	45,5
Acauã Novo	114,1	77,3	22,7	13,9	79,5	20,5	46,2	46,2	53,8	22,7	49,8	50,2	39,5	52,1	47,9
Arara	78,7	66,3	33,7	14,0	84,3	15,7	50,2	50,2	49,8	25,1	48,3	51,7	42,2	36,7	63,3
Asabranca	80,6	69,5	30,5	13,8	84,4	15,6	48,0	48,0	52,0	27,7	57,7	42,3	38,8	48,4	51,6
Bourbon Amarelo J9	122,0	64,5	35,5	20,0	82,2	17,8	48,2	48,2	51,8	29,7	55,2	44,8	38,8	42,9	57,1
Catiguá MG2	80,8	68,2	31,8	17,9	79,1	20,9	56,4	56,4	43,6	26,7	54,5	45,5	36,4	44,3	55,7
Catuai Amarelo 32	104,4	69,6	30,4	21,4	82,4	17,6	49,3	49,3	50,7	29,3	51,6	48,4	43,3	44,5	55,5
Catuaí Vermelho IAC 99	132,1	74,6	25,4	22,3	86,3	13,7	54,2	54,2	45,8	29,4	56,7	43,3	42,1	48,3	51,7
Catucaí Amarelo L 24/137	110,0	78,9	21,1	16,8	87,5	12,5	51,1	51,1	48,9	24,3	55,2	44,8	35,6	45,6	54,4

Catucaí Amarelo L2SL	117,4	72,4	27,6	20,4	90,3	9,7	53,7	53,7	46,3	26,2	52,2	47,8	47,5	41,6	58,4
Catucaí Vermelho (Guará)	92,1	66,6	33,4	19,1	80,3	19,7	48,3	48,3	51,7	28,7	58,1	41,9	35,8	41,6	58,4
IAC 125 RN	88,5	66,4	33,6	12,2	84,1	15,9	65,4	65,4	34,6	28,4	53,1	46,9	42,2	42,4	57,6
IBC 12 19F/6	130,6	78,7	21,3	17,3	83,9	16,1	62,2	62,2	37,8	28,2	54,5	45,5	50,0	52,2	47,8
IPR 100	102,7	71,1	28,9	17,7	82,9	17,1	49,2	49,2	50,8	26,3	50,5	49,5	45,0	48,1	51,9
IPR 103	85,0	66,5	33,5	20,9	87,5	12,5	55,3	55,3	44,7	27,2	53,2	46,8	46,5	52,8	47,2
IPR 107	117,6	69,5	30,5	14,2	87,9	12,1	62,4	62,4	37,6	28,5	49,3	50,7	47,7	38,9	61,1
MGS Aranãs	94,0	68,4	31,6	18,8	89,7	10,3	47,1	47,1	52,9	28,0	52,5	47,5	43,5	47,5	52,5
MGS Paraíso 2	98,0	68,4	31,6	18,3	82,7	17,3	45,4	45,4	54,6	25,6	50,0	50,0	37,7	45,5	54,5
MGS Paraíso 3	89,0	68,5	31,5	18,4	89,4	10,6	49,6	49,6	50,4	26,7	51,7	48,3	40,3	43,3	56,7
MGS Paraíso 4	110,3	69,3	30,7	17,5	84,1	15,9	55,7	55,7	44,3	26,3	50,7	49,3	46,6	46,1	53,9
Rouxinol	101,3	73,9	26,1	21,9	83,4	16,6	53,9	53,9	46,1	23,4	50,1	49,9	48,0	51,1	48,9
Sarchimor MG 8840	75,7	62,7	37,3	17,3	81,2	18,8	59,1	59,1	40,9	26,7	54,0	46,0	42,0	47,2	52,8
Topazio MG 1190	89,3	72,0	28,0	18,8	93,3	6,7	56,7	56,7	43,3	26,7	55,9	44,1	39,6	49,8	50,2
Minimum	75,7	62,7	16,8	12,2	76,3	6,7	45,4	45,4	34,6	22,7	48,3	41,9	35,6	36,7	45,5
Maximum	162,3	83,2	37,3	22,3	93,3	23,7	65,4	65,4	54,6	29,7	58,1	51,7	50,0	54,5	63,3
Average	102,8	70,8	29,2	17,6	84,2	15,8	52,7	52,7	47,3	26,9	53,2	46,8	42,5	46,4	53,6

Table 4. Macronutrient export in the fruit and distribution in the husk and bean of different coffee cultivars (*Coffea arabica*), per 60-kg bag.

Cultivar	N			P			K			Ca			Mg			S		
	Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean
	kg saca^{-1}																	
Acauã 365	2,01	0,77	1,25	0,12	0,05	0,08	2,17	1,20	0,97	0,19	0,14	0,05	0,15	0,04	0,11	0,14	0,06	0,08
Acauã CV8	2,02	0,78	1,24	0,13	0,05	0,07	2,09	1,09	1,00	0,21	0,14	0,07	0,15	0,04	0,11	0,14	0,06	0,08
Acauã Novo	2,01	0,76	1,25	0,12	0,04	0,08	2,26	1,22	1,04	0,20	0,14	0,06	0,16	0,05	0,11	0,14	0,06	0,08

Arara	2,03	0,76	1,27	0,12	0,04	0,08	2,01	1,11	0,90	0,22	0,15	0,07	0,15	0,04	0,11	0,14	0,06	0,08
Asabranca	2,05	0,78	1,27	0,11	0,05	0,06	2,02	1,11	0,91	0,20	0,13	0,07	0,14	0,04	0,10	0,13	0,06	0,07
Bourbon Amarelo J9	2,05	0,78	1,27	0,14	0,05	0,09	2,17	1,29	0,88	0,24	0,16	0,07	0,16	0,05	0,12	0,15	0,07	0,08
Catiguá MG2	1,98	0,75	1,23	0,12	0,05	0,08	1,96	0,99	0,97	0,20	0,14	0,06	0,16	0,05	0,11	0,14	0,06	0,08
Catuaí Amarelo 32	2,02	0,77	1,25	0,13	0,05	0,08	2,02	1,10	0,92	0,23	0,16	0,08	0,15	0,05	0,10	0,15	0,07	0,08
Catuaí Vermelho IAC 99	2,00	0,75	1,25	0,14	0,06	0,08	2,16	1,24	0,92	0,22	0,16	0,06	0,16	0,05	0,11	0,15	0,07	0,08
Catucaí Amarelo L 24/137	2,00	0,74	1,26	0,11	0,04	0,07	2,10	1,33	0,77	0,20	0,14	0,06	0,14	0,04	0,10	0,14	0,06	0,08
Catucaí Amarelo L2SL	2,02	0,75	1,27	0,14	0,06	0,08	2,05	1,20	0,84	0,22	0,15	0,07	0,14	0,04	0,10	0,14	0,06	0,08
Catucaí Vermelho (Guará)	1,99	0,74	1,24	0,14	0,06	0,08	2,04	1,15	0,89	0,18	0,12	0,06	0,16	0,05	0,11	0,14	0,07	0,08
IAC 125 RN	1,99	0,75	1,24	0,12	0,04	0,08	2,06	1,16	0,90	0,19	0,11	0,07	0,15	0,04	0,11	0,13	0,06	0,07
IBC 12 19F/6	2,01	0,76	1,25	0,14	0,06	0,08	2,13	1,29	0,84	0,22	0,15	0,06	0,15	0,05	0,10	0,14	0,07	0,07
IPR 100	2,01	0,76	1,24	0,12	0,05	0,07	1,90	1,03	0,88	0,20	0,14	0,06	0,14	0,04	0,10	0,14	0,06	0,08
IPR 103	2,01	0,76	1,25	0,13	0,06	0,08	2,15	1,21	0,94	0,23	0,17	0,06	0,15	0,05	0,11	0,15	0,07	0,08
IPR 107	1,99	0,76	1,24	0,13	0,05	0,08	2,15	1,14	1,01	0,20	0,14	0,06	0,15	0,04	0,11	0,15	0,06	0,08
MGS Aranãs	1,98	0,75	1,23	0,14	0,05	0,08	2,14	1,18	0,96	0,22	0,16	0,06	0,16	0,04	0,12	0,15	0,07	0,08
MGS Paraíso 2	1,99	0,77	1,22	0,13	0,05	0,08	2,05	1,12	0,93	0,19	0,13	0,06	0,15	0,04	0,11	0,14	0,06	0,08
MGS Paraíso 3	2,03	0,79	1,24	0,14	0,07	0,07	2,02	1,13	0,89	0,21	0,14	0,07	0,16	0,05	0,11	0,14	0,06	0,08
MGS Paraíso 4	2,01	0,76	1,25	0,13	0,05	0,08	2,01	1,15	0,86	0,22	0,15	0,07	0,15	0,05	0,11	0,14	0,06	0,08
Rouxinol	2,06	0,79	1,28	0,13	0,05	0,08	2,09	1,21	0,88	0,20	0,15	0,06	0,15	0,04	0,11	0,14	0,07	0,08
Sarchimor MG 8840	1,99	0,76	1,23	0,12	0,04	0,08	2,00	1,08	0,92	0,22	0,17	0,06	0,15	0,04	0,11	0,14	0,06	0,08
Topazio MG 1190	2,01	0,76	1,26	0,12	0,05	0,07	2,07	1,18	0,89	0,20	0,15	0,05	0,15	0,04	0,10	0,14	0,07	0,07
Average	2,01	0,76	1,25	0,13	0,05	0,08	2,08	1,16	0,91	0,21	0,15	0,06	0,15	0,04	0,11	0,14	0,06	0,08

Table 5. Micronutrient export in the fruit and distribution in the husk and bean of different coffee cultivars (*Coffea arabica*), per 60-kg bag.

Cultivar	**Fe**			**B**			**Zn**			**Cu**			**Mn**		
	Export	**Husk**	**Bean**	**Export**	**Husk**	**Bean**	**Export**	**Husk**	**Bean**	**Export**	**Husk**	**Bean**	**Export**	**Husk**	**Bean**

	g saca^{-1}														
	-														
Acauã 365	9,74	8,10	1,64	0,83	0,63	0,20	0,56	0,28	0,28	1,66	0,95	0,71	2,59	1,28	1,32
Acauã CV8	5,44	3,94	1,50	0,95	0,76	0,20	0,60	0,28	0,32	1,59	0,87	0,72	2,87	1,56	1,31
Acauã Novo	6,85	5,29	1,55	0,83	0,66	0,17	0,65	0,30	0,35	1,36	0,68	0,68	2,37	1,23	1,13
Arara	4,72	3,13	1,59	0,84	0,71	0,13	0,72	0,36	0,36	1,50	0,73	0,78	2,53	0,93	1,60
Asabranca	4,84	3,36	1,48	0,83	0,70	0,13	0,67	0,32	0,35	1,66	0,96	0,70	2,33	1,13	1,20
Bourbon Amarelo J9	7,32	4,72	2,60	1,20	0,98	0,21	0,92	0,44	0,48	1,78	0,99	0,80	2,33	1,00	1,33
Catiguá MG2	4,85	3,31	1,54	1,07	0,85	0,22	0,55	0,31	0,24	1,60	0,87	0,73	2,18	0,97	1,22
Catuaí Amarelo 32	6,27	4,36	1,90	1,28	1,06	0,23	0,57	0,28	0,29	1,76	0,91	0,85	2,60	1,16	1,44
Catuaí Vermelho IAC 99	7,93	5,91	2,01	1,34	1,15	0,18	0,71	0,39	0,33	1,76	1,00	0,76	2,53	1,22	1,31
Catucaí Amarelo L 24/137	6,60	5,21	1,39	1,01	0,88	0,13	0,80	0,41	0,39	1,46	0,80	0,65	2,14	0,97	1,16
Catucaí Amarelo L2SL	7,05	5,10	1,95	1,22	1,11	0,12	0,82	0,44	0,38	1,57	0,82	0,75	2,85	1,19	1,67
Catucaí Vermelho (Guará)	5,53	3,68	1,85	1,15	0,92	0,23	0,67	0,32	0,35	1,72	1,00	0,72	2,15	0,89	1,25
IAC 125 RN	5,31	3,53	1,78	0,73	0,61	0,12	0,74	0,48	0,26	1,70	0,90	0,80	2,53	1,07	1,46
IBC 12 19F/6	7,84	6,17	1,67	1,04	0,87	0,17	0,75	0,47	0,28	1,69	0,92	0,77	3,00	1,57	1,43
IPR 100	6,16	4,38	1,78	1,06	0,88	0,18	0,57	0,28	0,29	1,58	0,80	0,78	2,70	1,30	1,40
IPR 103	5,10	3,39	1,71	1,26	1,10	0,16	0,61	0,34	0,28	1,63	0,87	0,77	2,79	1,48	1,32
IPR 107	7,05	4,90	2,15	0,85	0,75	0,10	0,85	0,53	0,32	1,71	0,84	0,87	2,86	1,12	1,75
MGS Aranãs	5,64	3,86	1,78	1,13	1,01	0,12	0,69	0,32	0,36	1,68	0,88	0,80	2,61	1,24	1,37
MGS Paraíso 2	5,88	4,02	1,86	1,10	0,91	0,19	0,61	0,28	0,33	1,53	0,77	0,77	2,26	1,03	1,23
MGS Paraíso 3	5,34	3,66	1,68	1,10	0,99	0,12	0,58	0,29	0,29	1,60	0,83	0,77	2,42	1,05	1,37
MGS Paraíso 4	6,62	4,59	2,03	1,05	0,88	0,17	0,72	0,40	0,32	1,58	0,80	0,78	2,80	1,29	1,51
Rouxinol	6,08	4,49	1,59	1,31	1,10	0,22	0,57	0,31	0,26	1,41	0,70	0,70	2,88	1,47	1,41
Sarchimor MG 8840	4,54	2,85	1,70	1,04	0,84	0,19	0,77	0,45	0,31	1,60	0,87	0,74	2,52	1,19	1,33
Topazio MG 1190	5,36	3,86	1,50	1,13	1,05	0,08	0,74	0,42	0,32	1,60	0,89	0,71	2,38	1,18	1,19
Average	6,17	4,41	1,76	1,06	0,89	0,16	0,69	0,36	0,32	1,61	0,86	0,75	2,55	1,19	1,36

Table 6. Regression models of nutrient export in coffee fruits as a function of estimated productivity (bags ha^{-1})

Nutrient	Regression Model	R^2
N	$\hat{y}$ = 1,6929 + 1,9669** x	0,995
P	$\hat{y}$ = − 0,2361 + 0,1342** x	0,869
K	$\hat{y}$ = − 3,4784 + 2,1645** x	0,950
Ca	$\hat{y}$ = 0,3098 + 0,2003** x	0,821
Mg	$\hat{y}$ = 0,4791 + 0,1398** x	0,905
S	$\hat{y}$ = - 0,5184 + 0,1543** x	0,951
Zn	$\hat{y} = -6{,}5535 + 0{,}8525^{**}\ x$	0,630
Cu	$\hat{y} = -5{,}9206 + 1{,}7662^{**}\ x$	0,872
Mn	$\hat{y} = -30{,}617 + 3{,}3391^{**}\ x$	0,838

Table 7. Nutrient export values expressed per hectare for three yield levels (40, 70, and 100 bags ha^{-1}), divided into husk and bean contributions

Nutrient	Fm(1)	Productivity (Bags ha^{-1})								
		40			70			100		
		Export	Husk	Bean	Export	Husk	Bean	Export	Husk	Bean
	kg saca^{-1}	kg ha^{-1}								
N	1.97	80,40	30,47	49,93	140,70	53,33	87,37	201,00	76,18	124,82
P	0,13	9,20	3,66	5,54	16,10	6,41	9,69	23,00	9,15	13,85
K	2,16	83,20	46,59	36,61	145,60	81,54	64,06	208,00	116,48	91,52
Ca	0,20	8,40	5,85	2,55	14,70	10,23	4,47	21,00	14,62	6,38
Mg	0,14	6,00	1,78	4,28	10,50	3,11	7,50	15,00	4,44	10,71
S	0,15	5,60	2,54	3,06	9,80	4,45	5,35	14,00	6,36	7,64
		g ha^{-1}								
Zn	0,85	27,60	14,55	13,05	48,30	25,45	22,85	69,00	36,36	32,64
Cu	1,77	64,40	34,26	30,14	112,70	59,96	52,74	161,00	85,65	75,35
Mn	3,34	102,00	47,33	54,67	178,50	82,82	95,68	255,00	118,32	136,68

(1) Fm = Multiplication factor or slope coefficient.

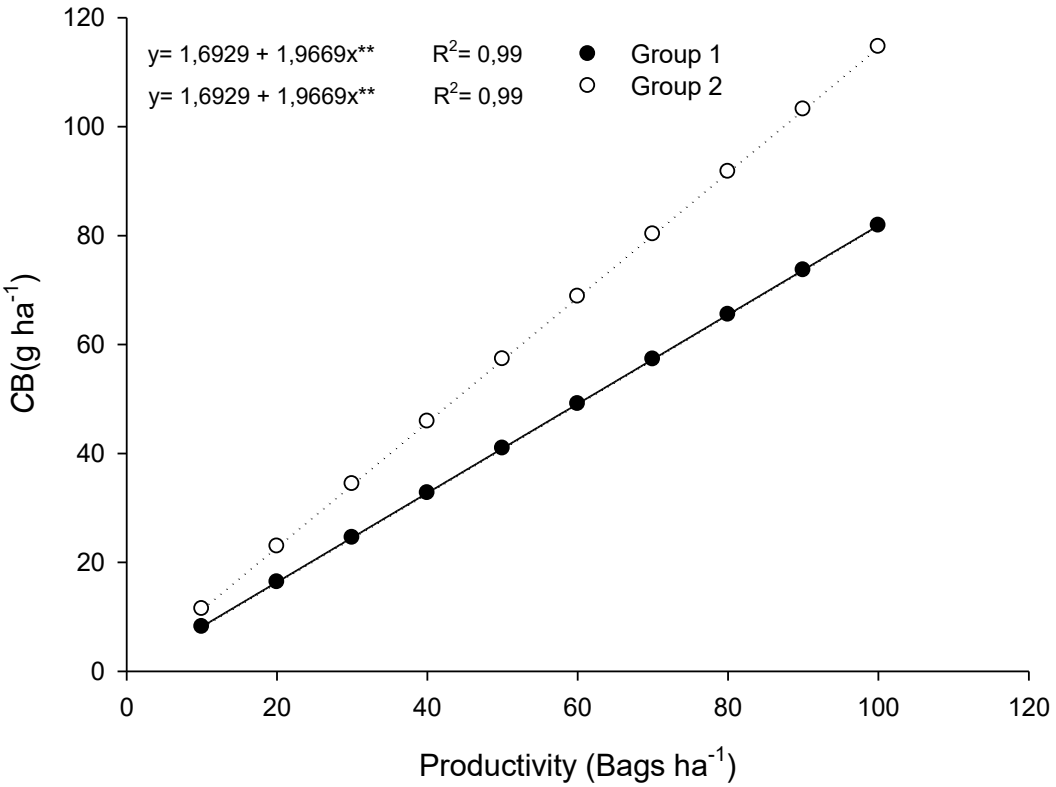

Figure 2. Clustering of coffee cultivars with similar nutrient export in the fruit as a function of productivity. Group 1: IAC 125 RN; Asabranca; Acauã 365; Acauã Novo; Arara; IPR 107; Acauã CV8. Group 2: Catucaí Amarelo L 24/137; Sarchimor MG 8840; IBC 12 19F/6; MGS Paraíso 4; IPR 100; Catiguá MG2; MGS Paraíso 2; MGS Paraíso 3; Topazio MG 1190; MGS Aranãs; Catucaí Vermelho (Guará); Bourbon Amarelo J9.Catucaí Amarelo L2SL; IPR 103; Catuaí Amarelo 32; Rouxinol; Catuaí Vermelho IAC 99.

5. DISCUSSION

Nutrient export in coffee fruits was similar among the 24 cultivars evaluated in the Cerrado Mineiro region, indicating that nutrient management for replenishment during the production phase should be guided primarily by quantitative factors (yield) rather than qualitative ones (cultivar). The exception was observed for B and Fe, where some cultivars were more or less efficient in the use of these nutrients. These results contribute to nutrient balance modeling and fertilization recommendations, especially within the context of the nutrient restitution concept.

Similarly, the results confirm that coffee fruits represent a major nutrient sink, accounting for approximately 50% of the plant's total dry matter (Garcia et al., 2009). This finding is highly relevant for formulating more accurate fertilization recommendations according to different productivity levels, enabling more precise nutrient management throughout the crop cycle.

The analyses showed that the coffee husk contains significant amounts of nutrients, particularly K and Ca, and a higher proportion of micronutrients compared to the bean, reinforcing its potential as an organic fertilizer (Garcia et al., 2009; Laviola et al., 2007). However, in many farms, this by-product is discarded, leading to the loss of these nutrients. Returning the husk to the soil may represent an efficient strategy to reduce fertilizer costs—especially during periods of high prices—and to improve soil organic matter and fertility (Matiello et al., 2016; Quaggio et al., 2022). Nevertheless, the nutritional composition of the husk can vary among cultivars, particularly for B and Fe, and should be considered in fertilization planning.

The substantial nutrient accumulation in coffee fruits observed in this study results from redistribution processes and the plant's physiological needs, which intensify after flowering. During fruit development, nutrient demands vary considerably. According to Matiello (2005), nutrient requirements are relatively low during the "chumbinho" (pinhead) stage, but increase significantly during the stages of expansion, grain filling, and maturation, as the fruits become preferential nutrient sinks within the plant.

Matiello (2016) estimated that for each bag of coffee produced, the coffee tree requires 6.2 kg of N, 0.6 kg of P_2O_5, 5.9 kg of K_2O, 2.14 kg of Ca, 1.15 kg of Mg, and 0.3 kg of S. In the present study, it was observed that approximately 2.0 kg of N, 0.12 kg of P, 2.1 kg of K, 0.20 kg of Ca, and 0.15 kg of Mg were specifically required for the production of beans

across the different cultivars. Considering the variation in nutrient demand during the fruit development phases, it is essential not only to know the nutrient doses required but also to understand the total nutrient export by the plant relative to its yield. This enables more efficient and sustainable nutrient management, tailoring fertilization practices to the specific needs of the crop.

The results demonstrated a linear correlation between nutrient export by the coffee fruits and yield for most elements, suggesting that as yield increases, so does the quantity of nutrients exported by the fruits. This aligns with the concept that higher-yielding cultivars tend to demand and export more nutrients, which must be considered in nutrient management (Laviola et al., 2009).

However, exceptions were observed for the micronutrients Fe and B. In the case of Fe, the statistical analysis (Scott–Knott test at 10%) indicated no significant differences among cultivars, resulting in a relatively uniform export of this element across genotypes. Consequently, Fe was the only nutrient for which no adjustment was performed, and it was not considered in the fertilization recommendation plan. On average, cultivars exported approximately 6.5 g of Fe per 60-kg processed bag.

For B, in contrast, nutrient export was not linearly related to yield, showing greater variability among cultivars. This suggests that B uptake and export are influenced by specific plant traits, soil interactions, and possible nutrient imbalances (Laviola et al., 2007). Such complexity requires a differentiated management approach to avoid deficiencies or toxicities that could compromise plant development or grain quality (Martinez et al., 2014).

The regression models developed for nutrient export allow for more precise estimations of nutrient requirements based on yield, supporting more efficient and cultivar-specific fertilization recommendations (De Carvalho et al., 2004). This distinction between cultivars with linear responses and those with more complex nutrient dynamics can also help select varieties better suited to specific soil and climatic conditions—especially in regions such as the Cerrado Mineiro—where productivity and coffee quality are strongly influenced by proper nutrient management (Martinez et al., 2014).

6. CONCLUSION

The export of nutrients by coffee fruits in the Cerrado Mineiro is more strongly influenced by yield levels than by genotypic differences among cultivars. Among the nutrients analyzed, only B exhibited significant variability as a function of cultivar, indicating genotype-specific efficiencies in the uptake and allocation of these micronutrients.

N, P, and Mg were predominantly allocated to the coffee beans, whereas K, Ca, and the majority of micronutrients were found in higher concentrations in the fruit husk. This differential nutrient partitioning underscores the importance of considering both components, beans and husks, when estimating nutrient export and planning fertilization strategies.

Cultivars such as IAC 125 RN, Asabranca, Acauã 365, Acauã Novo, Arara, IPR 107, Acauã CV8, demonstrated higher efficiency in the use of boron, suggesting potential for more sustainable nutrient management.

These findings contribute to the refinement of fertilization recommendations based on nutrient balance models and reinforce the need to tailor nutrient management practices to both productivity targets and specific cultivar characteristics.

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Capitulo 4. Terraceamento para plantio de café em áreas montanhosas

1. INTRODUÇÃO

A cafeicultura brasileira representa cerca de 30% da produção mundial, sendo uma atividade de grande relevância social, econômica e ambiental, especialmente na região Sudeste, onde se concentram as principais áreas produtoras (CONAB, 2023). A produção de *Coffea arabica* L. em regiões montanhosas do país é expressiva, particularmente nos estados de Minas Gerais, Espírito Santo e São Paulo (Carvalho, 2008). Essas áreas apresentam condições edafoclimáticas favoráveis ao cultivo do cafeeiro, com altitudes elevadas, temperaturas amenas e solos bem drenados, que resultam em cafés de alta qualidade (Mesquita et al., 2016). No entanto, tais regiões também apresentam desafios agronômicos, sobretudo pela acentuada declividade do terreno, que dificulta a mecanização das operações agrícolas (Cordeiro et al., 2010).

A maioria dos tratos culturais, como a adubação, poda e colheita, ainda é realizada de forma manual nessas áreas. Contudo, a redução da oferta de mão de obra rural e o seu elevado custo têm comprometido a viabilidade da atividade, levando muitos produtores ao abandono da lavoura (Matiello et al., 2010). A mecanização surge, assim, como uma estratégia promissora para a sustentabilidade técnica e econômica da cafeicultura de montanha.

Estudos demonstram que a mecanização da lavoura pode reduzir os custos de produção em até 24% em comparação ao sistema exclusivamente manual, e em 7% em relação ao sistema semi-mecanizado (Pádua et al., 2000). Avanços no desenvolvimento de máquinas adaptadas ao relevo acidentado têm ampliado essa possibilidade, permitindo operações mecanizadas em terrenos com declividade de até 30% (Santinato et al., 2014; Ferreira Junior et al., 2016), e, mais recentemente, até 50%, com o uso de derriçadoras articuladas desenvolvidas por pesquisadores do Departamento de Engenheira Agrícola da Universidade Federal de Viçosa (Teixeiras e Moreira, 2020)

Contudo, práticas como o plantio “morro abaixo”, adotadas por alguns produtores na tentativa de facilitar a mecanização, aumentam o risco de erosão e a degradação dos recursos naturais, comprometendo a longevidade produtiva do sistema. Diante desse cenário, o terraceamento agrícola se destaca como uma alternativa viável para promover a mecanização em áreas de relevo acidentado, ao mesmo tempo em que conserva o solo e a água.

Trata-se de uma técnica milenar, já utilizada por civilizações como os Incas, que construíam terraços em curvas de nível para o cultivo em áreas andinas (Navarro, 2008). No

Brasil, os primeiros registros de uso dessa prática datam da década de 1930, no estado de São Paulo (Ferrarezi, 2009).

Na cafeicultura de montanha, o terraceamento do tipo patamar tem se mostrado especialmente promissor, permitindo o plantio em nível, o tráfego de máquinas e a colheita mecanizada, além de contribuir para o controle da erosão e o aumento da produtividade.

Este boletim técnico tem como objetivo apresentar fundamentos, orientações e experiências práticas sobre o uso do terraceamento na cafeicultura em áreas montanhosas, com vistas à promoção de sistemas mais produtivos, mecanizáveis e ambientalmente sustentáveis. Para tanto, serão utilizados exemplos da propriedade localizada na região das Matas de Minas, conduzidos pelo Departamento de Solos da Universidade Federal de Viçosa (Figura 1).

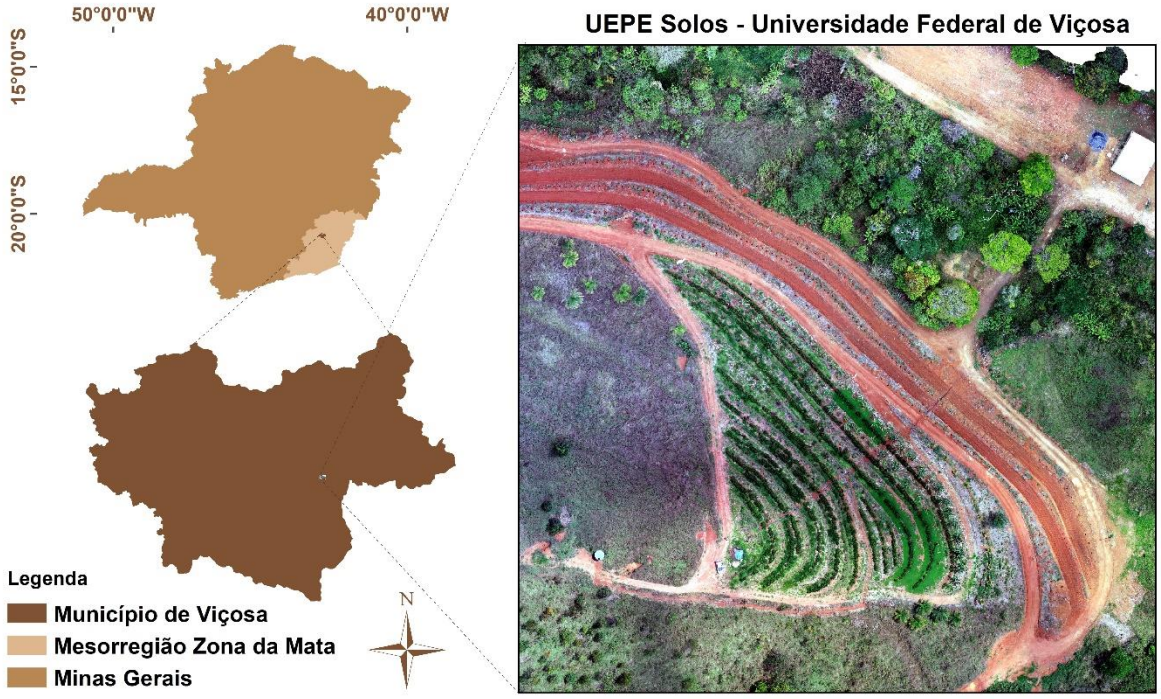

Figura 1. Localização da Unidade de Ensino, Pesquisa e Extensão em Solos (UEPE/Solos), vinculada ao Departamento de Solos da Universidade Federal de Viçosa (UFV).

FUNDAMENTOS PARA TERRACEAMENTO

A agricultura moderna enfrenta o desafio de conciliar produtividade agrícola com sustentabilidade ambiental, especialmente em regiões de relevo acidentado, como as montanhosas. Nesse contexto, as práticas conservacionistas constituem um conjunto de técnicas integradas cujo objetivo é promover a utilização racional dos recursos edáficos e hídricos, assegurando sua preservação a longo prazo.

De forma geral, essas práticas visam:

- Aumentar ou estabilizar a produtividade das culturas ao longo dos anos;
- Proteger os recursos naturais, especialmente do solo e a água;
- Prevenir a degradação da qualidade física, química e biológica do solo;
- Assegurar a viabilidade econômica da atividade agrícola;
- E manter um nível de aceitabilidade social, considerando as condições e a realidade dos agricultores.

Segundo Ferrarezi, (2009) As práticas conservacionistas do solo podem ser agrupadas em três categorias principais:

- Práticas de caráter vegetativo;
- Práticas de caráter edáfico;
- Práticas de caráter mecânico.

A eficácia dessas práticas aumenta significativamente quando são integradas entre si, formando um sistema conservacionista completo e sinérgico, como no caso do terraceamento, que depende do bom manejo das demais dimensões para alcançar seu pleno potencial.

Práticas de caráter vegetativo

As práticas vegetativas têm como principal função proteger a superfície do solo contra o impacto direto das gotas de chuva, reduzir a velocidade do escoamento superficial e promover a estruturação biológica do solo, além de favorecer a ciclagem de nutrientes. Exemplos incluem:

- Uso de plantas de cobertura entre as linhas do cafeeiro;
- Emprego de genótipos adaptados às condições edafoclimáticas locais;

- Planejamento da época de preparo do solo e plantio, considerando o regime pluviométrico e o tipo de solo;
- Adoção de espaçamentos adequados, favorecendo o sombreamento e a cobertura do solo;
- Manejo integrado de plantas espontâneas, pragas e doenças, com vistas à manutenção da cobertura vegetal e saúde do agroecossistema.

Práticas de caráter edáfico

Essas práticas estão relacionadas ao uso racional do solo enquanto recurso produtivo e buscam melhorar suas condições físicas, químicas e biológicas. Dentre elas, destacam-se:

- Planejamento adequado do uso da terra, com base na aptidão agrícola das diferentes unidades de relevo;
- Uso eficiente de corretivos e condicionador do solo, como calcário e gesso agrícola, visando melhorar a estrutura e a fertilidade;
- Fertilização mineral e orgânica equilibrada, promovendo o suprimento adequado de nutrientes, e a atividade biológica.

Práticas de caráter mecânico

As práticas mecânicas consistem em intervenções físicas no terreno com o intuito de controlar o fluxo da água, minimizar a erosão laminar e facilitar a mecanização agrícola. Nessa categoria, incluem-se:

- Locação adequada de estradas e carreadores, com drenagem superficial bem dimensionada;
- Construção de terraços e patamares, que promovem a ruptura da declividade do terreno, reduzem a velocidade da enxurrada e aumentam a infiltração de água no solo;

Consequentemente, essas práticas contribuem para a retenção de nutrientes no perfil, evitando perdas por lixiviação e erosão, e favorecendo um manejo conservacionista e produtivo da lavoura cafeeira. A Figura 2 ilustra o levantamento topográfico da área experimental antes e após a construção dos terraços, evidenciando a redução da declividade e a adequação do relevo para práticas conservacionistas e mecanizáveis.

Em conjunto, essas três categorias de práticas formam a base para um sistema de produção sustentável, no qual o terraceamento se destaca não apenas como uma técnica de conservação do solo, mas também como um facilitador da mecanização e estratégia de adaptação da cafeicultura ao relevo montanhoso. Sua implementação, no entanto, deve ser precedida por um planejamento técnico detalhado, considerando as características do solo, da cultura e do ambiente local.

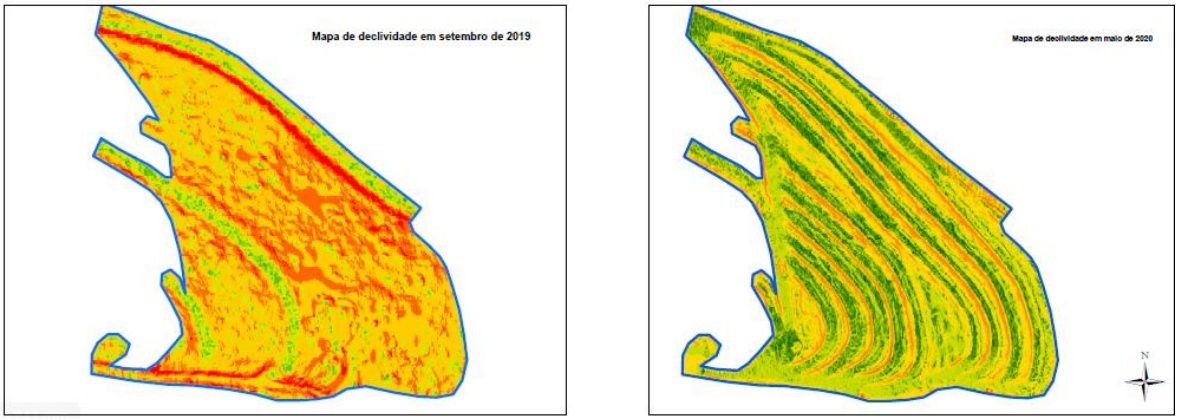

Figura 2. Levantamento topográfico da declividade da área experimental, realizado antes e após a construção dos terraços tipo patamar. da Unidade de Ensino, Pesquisa e Extensão em Solos (UEPE/Solos), vinculada ao Departamento de Solos da Universidade Federal de Viçosa (UFV).

TIPOS DE TERRAÇOS E A ESCOLHA DOS TERRAÇOS TIPO PATAMAR

A definição do tipo de terraceamento a ser adotado em áreas agrícolas deve considerar uma série de fatores técnicos e ambientais, como declividade do terreno, profundidade e textura do solo, regime pluviométrico, tipo de cultura, nível de mecanização desejado e risco de erosão.

Os terraços podem ser classificados, de forma geral, em três categorias:

- **Terraços em nível:** voltados principalmente para a conservação da água, pois reduzem a velocidade da enxurrada e aumentam a infiltração, mas apresentam menor eficiência em terrenos com declividade elevada.
- **Terraços em desnível:** indicados para áreas com problemas de drenagem, pois conduzem o excesso de água superficial para estruturas de escoamento; são menos indicados para culturas perenes e mecanização.
- **Terraços tipo patamar (ou terraços em bancada):** consistem na modificação do relevo original por meio da construção de plataformas ou degraus planos ou com leve inclinação, permitindo a mecanização de tratos culturais e da colheita em áreas com elevada declividade.

No caso específico da cafeicultura em regiões montanhosas, onde a declividade geralmente excede 20%, o terraceamento do tipo patamar tem se destacado como a alternativa mais viável e eficiente (Zonta et al., 2012). A escolha pelos terraços tipo patamar é justificada principalmente pela necessidade de adaptação da lavoura à mecanização e pela redução expressiva do risco de erosão hídrica, além de melhorar significativamente as condições operacionais e logísticas da propriedade rural.

A seguir, serão detalhadas as características técnicas e construtivas dos terraços tipo patamar, destacando-se sua viabilidade prática, impactos agronômicos, econômicos e ambientais, bem como exemplos aplicados na cafeicultura das Matas de Minas na Unidade de Extensão e Pesquisa do Departamento de Solos da Universidade Federal de Viçosa.

Escolha e avaliação da área

A implementação de sistemas de terraceamento em áreas montanhosas deve ser precedida por um planejamento técnico criterioso, com ênfase na caracterização do relevo e da aptidão agrícola dos solos. O levantamento topográfico da área é etapa essencial, pois fornece

as cotas altimétricas e os gradientes de declive, parâmetros que norteiam o traçado das curvas de nível, fundamentais para a correta locação de terraços, estradas e carreadores (Figura 3).

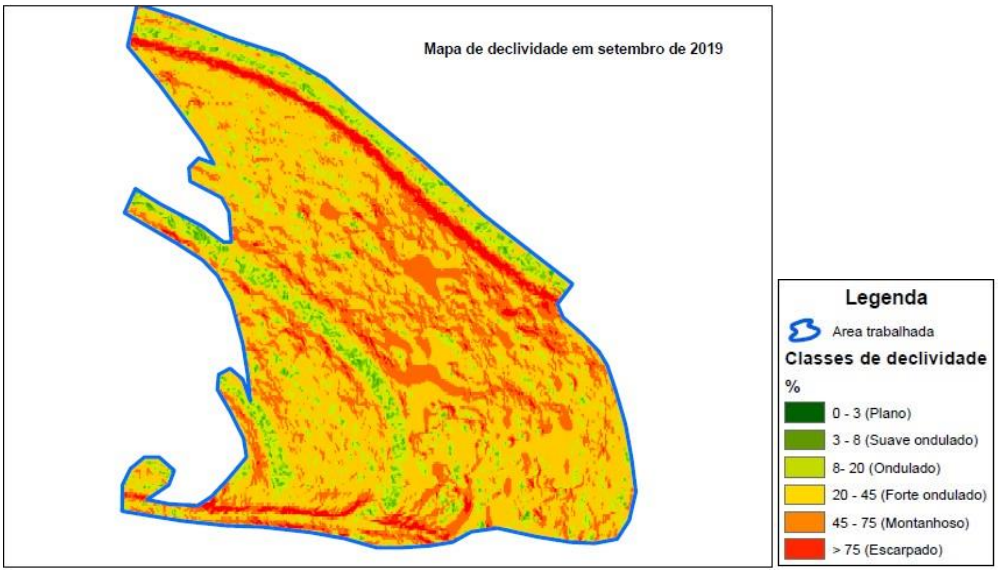

Figura 3. Levantamento topográfico realizado na área experimental da Unidade de Ensino, Pesquisa e Extensão em Solos (UEPE/Solos), vinculada ao Departamento de Solos da Universidade Federal de Viçosa (UFV).

A declividade do terreno, expressa em porcentagem, representa o grau de inclinação da superfície e exerce influência direta sobre processos erosivos, viabilidade de mecanização e escolha de culturas (Souza et al., 2021; Nanni et al., 2005; Ramalho & Beek, 1995). Ela pode ser determinada por diversos métodos, como nível de mangueira, nível óptico, clinômetro, drones com sensores altimétricos ou modelos digitais de elevação (MDE), conforme a escala e os recursos disponíveis. A classificação do relevo com base na declividade, apresentada na Tabela 1, auxilia no diagnóstico da área e na tomada de decisão sobre o tipo de intervenção mais adequada.

Declividade (%)	**Classe**
0 – 3	Plano
3 – 8	Suave - Ondulado
8 – 20	Ondulado
20 – 45	Fortemente ondulado
45 – 75	Montanhoso
>75	Fortemente montanhoso

Fonte: Adaptado de Ramalho e Beek, 1995.

No caso da área experimental em questão, a declividade média supera 20%, caracterizando um relevo fortemente ondulado. Nessa condição, o uso de terraços tipo patamar é altamente recomendado, tanto para controle da erosão hídrica quanto para viabilizar a mecanização do cultivo cafeeiro.

As curvas de nível, que interligam pontos com a mesma altitude, são instrumentos indispensáveis no planejamento conservacionista, pois orientam o preparo do solo, o plantio em nível de culturas perenes e a disposição de estruturas hidráulicas e de tráfego (Wadt, 2004; Tenório & Seixas, 2008). A leitura adequada dessas curvas permite antecipar o comportamento do escoamento superficial e adotar estratégias de controle compatíveis com o microrelevo local.

A eficiência de um sistema de terraceamento depende da sua integração com outras práticas conservacionistas, como o plantio em nível, a manutenção da cobertura do solo, a rotação de culturas e o manejo adequado da fertilidade (Pruski, 2009). Vale ressaltar que nem todos os solos são aptos para o terraceamento. Em solos muito pedregosos, rasos, com baixa capacidade de infiltração ou subsolos adensados, os custos de construção e manutenção dos terraços podem ser proibitivos, inviabilizando a prática (Bertoni & Lombardi Neto, 1985).

CONSTRUÇÃO DE TERRAÇOS DO TIPO PATAMAR EM ÁREAS MONTANHOSAS PARA O CULTIVO DE CAFÉ

O terraceamento é uma técnica agrícola de conservação do solo que consiste no parcelamento de áreas inclinadas por meio da construção de rampas transversais ao maior declive do terreno. Sua estrutura básica é composta por um dique e um canal, com a finalidade de reter e infiltrar a água das chuvas em terraços em nível, ou escoá-la lentamente para áreas adjacentes nos terraços em desnível (Vital e Resck, 2002). Em regiões montanhosas produtoras de café, o terraceamento deve seguir as curvas de nível, sendo o terraço do tipo patamar o mais indicado, em função da declividade acentuada. Esse tipo de terraço é construído por meio da movimentação de terra com cortes e aterros, formando degraus horizontais ao longo da encosta (Bassani et al., 2023).

Antes da construção dos terraços, é essencial realizar a amostragem do solo da área para análises físicas e químicas, com coletas nas profundidades de 0–20 cm e 20–40 cm, conforme a divisão de glebas. Com base nos resultados dessas análises, serão recomendadas a calagem, a adubação e o estabelecimento de culturas de cobertura.

O preparo da área deve ser feito em período seco, visando minimizar a movimentação excessiva de terra. É importante evitar o acúmulo de água proveniente de estradas e carreadores, bem como promover rapidamente a reconstituição da cobertura vegetal com as primeiras chuvas.

A calagem deve ser aplicada em toda a superfície da área, com incorporação preferencialmente realizada com grade de discos na parte plana do patamar. A dose de calcário deve seguir as recomendações específicas para a cultura e para a região, conforme as análises de solo (Alvarez et al., 1999). O uso de gesso agrícola e resíduos orgânicos como compostagem, cama de frango e esterco curtido é também altamente recomendável nesta etapa.

Cada patamar deve possuir leve inclinação para o seu interior, com a construção de um pequeno dique no bordo inferior para evitar o escoamento superficial de água entre terraços, prevenindo erosão nos taludes. Nas laterais dos terraços devem ser construídas estradas de acesso para o tráfego de máquinas e execução das operações agrícolas (Figura 4). Em áreas com alta declividade, é indicada a construção de caixas de retenção ao longo das estradas, em sentido oposto ao do patamar, para conter o escoamento pluvial, reduzir perdas de solo e reter água por mais tempo no sistema (Zonta et al., 2012).

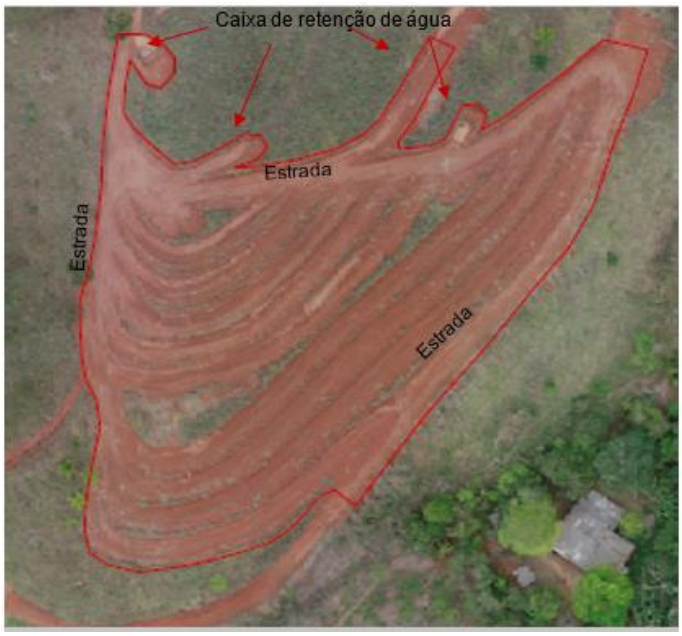

Figura 4. Vista geral da área experimental da Unidade de Ensino, Pesquisa e Extensão em Solos (UEPE/Solos), vinculada ao Departamento de Solos da Universidade Federal de Viçosa, após a construção dos terraços do tipo patamar.

Segundo Pruski (2009), a escolha do tipo mais adequado de terraço depende da topografia, das características físico-hídricas do solo, das condições climáticas, da cultura implantada, do sistema de manejo e da disponibilidade de máquinas agrícolas. Para terrenos com declividade inferior a 8%, recomenda-se o uso de terraços de base larga; de 8–12%, base média; de 12–18%, base estreita; e acima de 18%, o tipo patamar, que é mais adequado a áreas montanhosas (Lombardi et al., 1991).

A Tabela 2 apresenta os valores médios de base e altura recomendados para os patamares em áreas declivosas destinadas ao cultivo de café. A altura média máxima do barranco de 1,5 m é recomendada para maior segurança. A escolha do espaçamento também depende do número de linhas de plantio (uma ou duas) e da possibilidade de adoção de colheita mecanizada ou manual.

Tabela 2. Valores médios de base e altura recomendados para os patamares destinadas ao cultivo de café.

Base do Patamar	**Altura do Patamar**	**Declividade do Terreno**
m	m	%
	≤ 0,8	≤ 32,0
2,5	0,8 - 1,0	32,0 - 40,0
	1,0 - 1,2	40,0 - 48,0

	≤ 0,8	≤ 26,0
3,0	0,8 - 1,0	26,0 - 33,0
	1,0 - 1,2	33,0 - 40,0
	≤ 0,8	≤ 20,0
4,0	0,8 - 1,0	20,0 - 25,0
	1,0 - 1,2	25,0 - 30,0

A movimentação de solo é realizada com cortes e aterros, com equipamentos pá carregadeira ou trator esteira, o que resulta em maior rendimento operacional em áreas maiores (Figura 5).

Figura 5. Utilização de pá carregadeira na construção do terraço tipo patamar, com base de 4,0 m de largura e altura média de 1,2 m, na área experimental.

Após a construção dos terraços, deve-se fazer a amostragem do solo do patamar para avaliação das condições químicas e físicas, novamente nas profundidades de 0–20 cm e 20–40 cm, para elaboração da recomendação de adubação de plantio e cobertura.

A calagem deve ser feita com base na análise do solo, com incorporação do calcário a pelo menos 20 -30 cm de profundidade na base do patamar. Da mesma forma, deve ser feita a aplicação de corretivo na parte declivosa do terraço para melhor estabelecimento das plantas de cobertura e culturas de consórcio. (Figura 6).

Figura 6. Aplicação de calcário na área terraceadas destinada ao plantio do cafeeiro.

Estabilização dos Terraços

A estabilização dos terraços é uma etapa fundamental para garantir a durabilidade da estrutura e evitar processos erosivos nas fases iniciais após a sua construção. A cobertura vegetal do talude e da base do patamar com espécies adaptadas é uma prática essencial que promove a proteção do solo contra o impacto direto das gotas de chuva, aumenta a infiltração de água e melhora a agregação e estruturação do solo (Cogo et al., 2003; Pruski, 2009).

A semeadura de plantas de cobertura deve ser realizada imediatamente após a movimentação de terra e a formação dos patamares, visto que o solo permanece exposto e suscetível à erosão laminar e à formação de sulcos, especialmente em períodos de chuvas intensas. A cobertura vegetal atua por meio da interceptação da água da chuva, do aumento da rugosidade superficial e, principalmente, pelo efeito consolidante do sistema radicular, que contribui para a estabilidade física do talude (Bonini e Alves, 2011; Volk e Congo, 2008).

Dentre as espécies mais indicadas para a cobertura de terraços, destacam-se:

- *Brachiaria ruziziensis*, pela alta produção de biomassa, sistema radicular denso, baixo custo de sementes e facilidade de dessecação;
- *Crotalária juncea*, que além de formar biomassa rapidamente, contribui com a fixação biológica de nitrogênio e efeito alelopático sobre plantas daninhas;
- *Arachis pintoi* (amendoim forrageiro), com crescimento rasteiro, boa cobertura do solo e elevada persistência, especialmente em áreas tropicais com alta umidade.

Na área experimental utilizada neste estudo, optou-se pela semeadura a lanço de *Brachiaria ruziziensis*, utilizando-se um espalhador costal da marca Guarany (Figura 7). Segundo Ceccon e Concenço (2014), essa espécie apresenta vantagens como:

- Baixo custo de aquisição de sementes (comparado a outras gramíneas forrageiras do mesmo gênero);
- Rápida recuperação após o estresse hídrico;
- Elevada formação de cobertura morta (palhada);
- Efeito supressor de plantas daninhas;
- Facilidade de controle com herbicidas não seletivos.

Figura 7. Semeadura de *Brachiaria ruziziensis* para estabilização dos terraços.

A calagem foi realizada previamente à semeadura da braquiária, conforme os resultados da análise química do solo e com base nas recomendações do Manual de Recomendações para o uso de corretivos e fertilizantes em Minas Gerais – 5ª Aproximação (Ribeiro et al., 1999). A adubação de plantio da planta de cobertura também foi conduzida seguindo as exigências nutricionais da espécie e a fertilidade inicial do solo.

Essa estratégia integrada de estabilização vegetativa é parte essencial do manejo conservacionista em áreas declivosas, permitindo o uso agrícola sustentável dessas regiões e reduzindo os riscos de degradação ambiental e perdas econômicas (Bertoni & Lombardi Neto, 1999; Santos et al., 2008).

Controle do crescimento das plantas de cobertura e plantio do café

Aproximadamente cinco meses após a semeadura da *Brachiaria ruziziensis*, foi realizada a primeira roçagem da cobertura vegetal com o objetivo de controlar o crescimento excessivo da forrageira e proporcionar aporte de material orgânico à superfície do solo, promovendo sua proteção contra impactos diretos da chuva e reduzindo perdas por erosão. A roçagem foi conduzida sempre que necessário, a fim de evitar competição por luz, água e nutrientes com a cultura de interesse econômico, neste caso, o cafeeiro.

Após o controle da cobertura, deve ser realizada a subsolagem na linha de plantio, a 40 – 60 cm de profundidade (Figura 8), com o objetivo de descompactar camadas subsuperficiais do solo, favorecendo o aprofundamento do sistema radicular do cafeeiro e a infiltração de água (Fernandes et al., 2012). Na sequência, deve aplicar calcário e gesso, conforme recomendação técnica, com o objetivo de correção da acidez e fornecimento de Ca, Mg e S na linha de plantio.

Figura 8. Base do patamar após a roçagem da cobertura vegetal e a realização da subsolagem na linha de plantio do cafeeiro.

O sulco de plantio foi aberto e a adubação de implantação realizada conforme os resultados das análises de solo, com base nas recomendações do Manual de Recomendações para o Uso de Corretivos e Fertilizantes em Minas Gerais – 5ª Aproximação (Ribeiro et al., 1999). Uma sugestão de adubação, por metro linear, corresponde:

- 300 g m^{-1} de calcário dolomítico,
- 150 g m^{-1} de gesso
- 5 -10 L m^{-1}de adubo orgânico (cama de frango, esterco, composto),
- 200 – 300 g m^{-1} de superfosfato simples (se optar pelo gesso, usar MAP 100 g m^{-1}) e
- 200 – 300 g m^{-1}de fosfato reativo.

O calcário, gesso e adubo orgânico devem ser misturados e incorporados ao solo. Na sequência, deve ser feita a aplicação do adubo fosfatado localizado a 20 – 30 cm de profundidade no centro do sulco de plantio. Esses insumos visam melhorar a fertilidade do solo na linha de plantio, fornecendo macro e micronutrientes essenciais ao estabelecimento inicial do cafeeiro, com destaque para o fósforo, que é fundamental para o desenvolvimento radicular na fase de implantação.

Considerando o caráter experimental da área, foram implantadas três cultivares de *Coffea arabica L.*: Catuaí (fruto vermelho, tradicional na Zona da Mata Mineira), Arara e Catucaí 24/137 (ambos com frutos amarelos e porte baixo), selecionadas por sua adaptabilidade às condições edafoclimáticas da região, resistência a doenças e boa performance agronômica (Carvalho et al., 2008).

O plantio foi realizado utilizando dois arranjos espaciais: linhas simples e linhas duplas (Figura 9). O espaçamento entre plantas foi de 0,50 m, adequado ao cultivo mecanizado, tanto para tratos culturais quanto para a colheita (Silveira et al., 2018). O uso de linhas duplas em terraços tipo patamar otimiza o aproveitamento da base do terraço, mantendo a densidade de semeadura por hectare igual a uma área não terraceadas, facilitando seu manejo.

Figura 9. Arranjos espaciais do cafeeiro em linhas simples e linhas duplas.

Manutenção da Área e Condução do Cafeeiro

O replantio das mudas foi realizado até 30 dias após o plantio inicial, assegurando o pegamento de 100% das plantas na área experimental. Essa prática é fundamental para garantir uniformidade no estande e evitar falhas que possam comprometer a produtividade por hectare.

Antes do plantio das mudas de café, foi realizado o controle de formigas cortadeiras com o uso de iscas granuladas contendo Sulfluramida como princípio ativo. O manejo prévio dessas pragas é essencial, visto que ataques logo após o transplantio podem causar mortalidade significativa de mudas, comprometendo o estabelecimento do cafeeiro. O controle fitossanitário (pragas e doenças) é conduzido com base no monitoramento da lavoura, de forma preventiva e com intervenções apenas quando forem observados os primeiros sinais de danos, conforme princípios do Manejo Integrado de Pragas (MIP). Essa abordagem evita aplicações desnecessárias, reduzindo custos e impactos ambientais (Caixeta et al., 2024).

A adubação de formação do cafeeiro no primeiro ano foi realizada em três parcelas, visando suprir adequadamente as exigências nutricionais das mudas durante a fase inicial de desenvolvimento. A primeira aplicação foi realizada 60 dias após o plantio, a segunda aos seis meses, e a terceira aos nove meses após o estabelecimento das plantas. No total, foram aplicados por planta 30 g da fórmula 20-05-20 (NPK), além de 20 mL de uma solução de micronutrientes composta por 500 g de sulfato de manganês ($MnSO_4 \cdot H_2O$), 500 g de sulfato de zinco ($ZnSO_4 \cdot 7H_2O$), 250 kg de sulfato de cobre ($CuSO_4 \cdot 5H_2O$) e 250 kg de ácido bórico (H_3BO_3), diluídos em 100 L de água para aplicação via solo.

Essa estratégia nutricional visa suprir as exigências iniciais da cultura do cafeeiro, com ênfase no fornecimento de nitrogênio e potássio, que são os nutrientes mais requeridos durante a fase vegetativa. Nos anos subsequentes, a adubação de cobertura passa a ser realizada em duas parcelas, ajustadas com base nos resultados das análises de solo e na avaliação do estado nutricional das plantas. Após o início da colheita, a adubação passa a considerar a reposição dos nutrientes exportados pelos grãos, a fim de manter o equilíbrio nutricional do sistema produtivo (Ribeiro et al., 1999).

Além das práticas nutricionais, foi realizada a desbrota manual de 3 a 4 vezes por ano, sempre que necessário, para eliminar ramos ortotrópicos (“ladrões”) e malformações. Essa prática de condução visa otimizar a arquitetura da planta, melhorando a aeração e a penetração

de luz no dossel, além de direcionar a energia para os ramos produtivos, favorecendo o crescimento equilibrado e a produtividade (Mesquita et al., 2016).

Consórcio de culturas

O consórcio de culturas é uma estratégia agronômica que visa otimizar o uso do espaço, luz solar, água e nutrientes, por meio do cultivo simultâneo, em uma mesma área, de duas ou mais espécies vegetais com diferentes arquiteturas, hábitos de crescimento e exigências fisiológicas. Esse sistema proporciona maior eficiência no uso dos recursos naturais, redução de riscos econômicos, e geração de renda ao longo do ano devido à diversidade de espécies cultivadas (Silva et al., 2022).

Nos taludes (ou "saias") dos terraços da área experimental, foram adotados diversos sistemas de consorciação com espécies frutíferas, como: apenas bananeiras; bananeiras intercalado com abacate ou cacau; (Figura 10). O consórcio com frutíferas perenes pode agregar valor à área e contribuir para o controle da erosão, desde que sejam adotadas práticas adequadas de manejo.

Figura 10. Consorcio de culturas no talude dos terraços, bananeiras e abacateiro.

A escolha das culturas deve considerar as condições edafoclimáticas locais, exigências nutricionais e hídricas, exigência de manejo, viabilidade de comercialização, disponibilidade de mão de obra e recursos financeiros. A definição do arranjo ideal de consórcio

deve ser feita com o apoio de um engenheiro agrônomo, visando garantir sustentabilidade agronômica e econômica ao sistema (Siqueira et al., 2020).

O plantio das frutíferas foi realizado após o pegamento das mudas do cafeeiro. As covas foram abertas com perfurador mecânico, com profundidade de 60 cm, seguidas de adubação de plantio com mistura formulada 6-30-6 e aplicação de cama de frango. Após o plantio, foi realizado o monitoramento e controle de formigas cortadeiras com iscas contendo Sulfluramida, visando à proteção das mudas.

É fundamental monitorar o crescimento das espécies consorciadas, especialmente das frutíferas perenes, como o abacateiro, para evitar sombreamento excessivo que possa comprometer a fotossíntese e o desenvolvimento do cafeeiro. Para isso, recomenda-se a realização de podas de formação e condução, com ênfase na limitação do crescimento vertical e estímulo ao desenvolvimento horizontal das fruteiras (Morais et al., 2009). Quando bem manejado, o sombreamento pode criar um microclima mais favorável ao cafeeiro e aos trabalhadores, amenizando temperaturas extremas e reduzindo a evapotranspiração. O espaçamento adotado para as frutíferas foi de 6 × 6 m, resultando em uma densidade de 270 plantas por hectare, permitindo geração de renda adicional e melhor aproveitamento da área.

Durante a execução das adubações de cobertura do cafeeiro, foram também adubadas as frutíferas, com o objetivo de otimizar o uso da mão de obra e atender às exigências nutricionais de ambas as culturas. Também foi realizado, ao longo do ano, o coroamento químico e mecânico próximo às mudas, para reduzir a competição por água e nutrientes.

Outro tipo de consórcio implementado na área experimental foi com plantas de cobertura. Na base do terraço, onde foi implantado o cafeeiro, foram estabelecidas duas estratégias distintas: a semeadura de braquiária (*brachiaria ruziziensis*) e o plantio de amendoim forrageiro (*Arachis pintoi*), conforme a finalidade do manejo.

As espécies de braquiária mais utilizadas nesse contexto são *decumbens*, *brizantha* e *ruziziensis*, pela elevada capacidade de produção de matéria seca, tolerância à seca, desenvolvimento radicular profundo, elevada eficiência na ciclagem de nutrientes e controle de plantas daninhas (Ragassi et al., 2013). O manejo da braquiária inclui capinas regulares na linha de plantio do cafeeiro, a fim de evitar competição direta entre as espécies (Figura 11).

Figura 11. Manejo da braquiária na linha do plantio do cafeeiro.

A utilização do amendoim forrageiro (*Arachis pintoi*) como planta de cobertura viva na cafeicultura apresenta múltiplos benefícios agroecológicos, com destaque para a supressão de plantas espontâneas, a melhoria da estrutura física e biológica do solo, o aumento da retenção de umidade e, principalmente, a fixação biológica de nitrogênio (FBN), por meio da simbiose com bactérias do gênero *Bradyrhizobium* (Espindola et al., 2006). Esse processo contribui significativamente para a redução ou até eliminação da necessidade de adubação mineral nitrogenada, favorecendo sistemas de produção mais sustentáveis e de menor custo.

O plantio das mudas de amendoim forrageiro foi realizado com espaçamento de 20 cm entre plantas, formando gradualmente um denso tapete vegetal (Figura 12). Ao longo do ciclo, foi feito o monitoramento da área e a retirada seletiva de plantas invasoras, além da realização de capinas manuais na linha do cafeeiro para evitar competição direta entre as espécies. Essa prática garante a convivência harmoniosa entre a leguminosa e o cafeeiro, mantendo o equilíbrio do sistema e preservando os benefícios agroecológicos do consórcio (Bergo et al., 2006; Chaves, 2001).

O amendoim forrageiro também contribui com a ciclagem de nutrientes, o aumento do teor de matéria orgânica no solo, o estímulo à macrofauna edáfica e a melhoria da infiltração de água (Perin et al., 2003). Sua adaptabilidade ao ambiente tropical úmido, persistência sob sombreamento parcial e baixa exigência de manejo tornam essa espécie uma das melhores alternativas de cobertura viva para o cultivo de café em sistemas sustentáveis (Santos, 2011).

Figura 12. Cobertura do solo com amendoim forrageiro

CONCLUSÃO

A construção de terraços agrícolas em áreas montanhosas representa uma importante estratégia de adaptação da cafeicultura ao relevo acidentado, promovendo maior eficiência no uso do solo e da água, além de facilitar as operações mecanizadas e reduzir significativamente os riscos de erosão. Apesar das vantagens agronômicas e ambientais associadas ao terraceamento, é essencial reconhecer que sua implantação envolve um investimento inicial elevado, exigindo, portanto, planejamento criterioso e adoção de práticas complementares que maximizem seu retorno ao longo do tempo.

Nesse contexto, o consórcio com culturas frutíferas e espécies de cobertura, como leguminosas e gramíneas, surge como uma alternativa promissora para diversificar a produção, gerar renda adicional ao produtor e acelerar a amortização dos custos estruturais. A escolha das espécies consorciadas deve considerar as condições edafoclimáticas locais, a demanda de mercado e a compatibilidade fisiológica com o cafeeiro, assegurando a sustentabilidade do sistema no longo prazo.

Por fim, destaca-se que o sucesso do cultivo em áreas terraceadas depende, sobretudo, do manejo adequado dos recursos edáficos e hídricos. A manutenção da qualidade física, química e biológica do solo, aliada ao uso racional da água e à conservação da cobertura vegetal, constitui a base para sistemas produtivos resilientes e de alta produtividade. Dessa forma, os terraços, mais do que estruturas de contenção, passam a ser instrumentos para o desenvolvimento de uma agricultura regenerativa, conservacionista e economicamente viável.

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SUPPLEMENTARY MATERIAL

Table S1. Characterization of different *Coffea arabica* cultivars.

Cultivar	Origin	Resistances	Attributes
Acauã 365	Cross between Mundo Novo IAC 388-17 and Sarchimor IAC 1668	Highly resistant to coffee leaf rust and moderately resistant to *Meloidogyne exigua*	High vigor, abundant branching, good adaptation to heat and drought, intermediate ripening, low stature
Acauã cv.8	Selected from Acauã 365 fields	Highly resistant to rust and moderately resistant to *M. exigua*	High vigor, abundant branching, good adaptation to heat and drought, intermediate ripening, and low to medium stature.
Acauã Novo	Selected from Acauã 365 fields	Highly resistant to rust and moderately resistant to *M. exigua*	High vigor, abundant branching, good adaptation to heat and drought, intermediate ripening, low to medium stature.
Arara	Cross between Sarchimor 1669-20 and Icatu Amarelo 2944	Resistant to rust, tolerant to Phoma and bacterial blight	High bean to fruit conversion ratio, high vigor and productivity, excellent response to pruning, strong fruit retention, older branches remain productive, late ripening, low stature
Asabranca Lav. 14-5	Selected from Acauã 365 fields	Highly resistant to rust and moderately resistant to *M. exigua*	High vigor, abundant branching, good adaptation to heat and drought, intermediate ripening, low to medium stature.
Bourbon Amarelo J9	Cross between Bourbon Vermelho and Amarelo from Botucatu	None	Low vigor, highly susceptible to diseases, early ripening, tall stature.

Catiguá MG2	Cross between Catuaí Amarelo IAC 86 and Timor Hybrid UFV 440-10	Resistant to rust	High vigor, excellent cup quality, intermediate ripening, low stature.
Catuaí Amarelo 32	Cross between Mundo Novo and Caturra	None	High productivity, slightly higher yield than the red Variety, tendency to defoliate under high crop load, intermediate ripening, and low stature.
Catuaí Vermelho IAC 99	Cross between Mundo Novo and Caturra	None	High productivity, tendency to defoliate under high crop load, intermediate ripening, low stature.
Catucaí Amarelo 24/137	Selected from Catucaí fields	Moderately tolerant to rust	Highly productive, early to intermediate ripening, low stature.
Catucaí Amarelo 2SL	Selected from Catucaí fields	Moderately tolerant to rust and tolerant to Phoma	Good productivity and vigor, uniform plants, intermediate ripening, low to medium stature.
Catucaí Vermelho 20/15 (Guará)	Selected from Catucaí fields	Mderately resistant to rust	High vigor, very productive, wider canopy, well adapted to warmer regions, mid to late ripening, low stature.
IAC 125 RN	Cross between Villa Sarchi and Timor Hybrid	Resistant to rust, *M. exigua* and bacterial blight	Good productivity, high demand for water and nutrients, early ripening, low stature.
IPR 100	Cross between Catuaí and a Hybrid of Catuaí with BA-10 coffee plant (75% Catuaí genetics)	Resistant to *M. paranaensis*, *M. incognita and M. exigua*e toletant to anthracnose	Tolerant to heat and drought, better adaptation to poor soils, late ripening, low stature.
IPR 103	Cross between Catuaí and Icatu	None	High rusticity and productivity, tolerant to heat

			and drought, better adaptation to poor soils, late ripening, low stature.
IPR 107	Cross between IAPAR 59 and Mundo Novo IAC 376-4	Highly resistant to rust	High productivity and rusticity, early to medium ripening, low stature.
MGS Aranãs	Cross between Icatu Vermelho IAC 3851-2 and Catimor UFV 1602-215	Moderately resistant to rust	High cup quality, intermediate ripening, low stature.
MGS Paraíso 2	Croos between Catuaí Amarelo IAC 30 and Timor hybrid UFV 445-46	Resistant to rust	Good vigor, very good cup quality, intermediate ripening, low stature.
Rouxinol	Selected from Catucaí Vermelho fields	Resistant to rust	Good vigor and productivity, intermediate ripening, low stature.
Sarchimor MG 8840	Cross between Villa Sarchi and Timor Hybrid	Resistant to rust	Large screen size, good cup quality, intermediate ripening, low stature.
Topázio MG 1190	Selected from a hybrid between Mundo Novo 515 and Catuaí Amarelo	None	Uniform plants, productivity similar to Catuaí, highly susceptible to rust, early ripening, low stature.