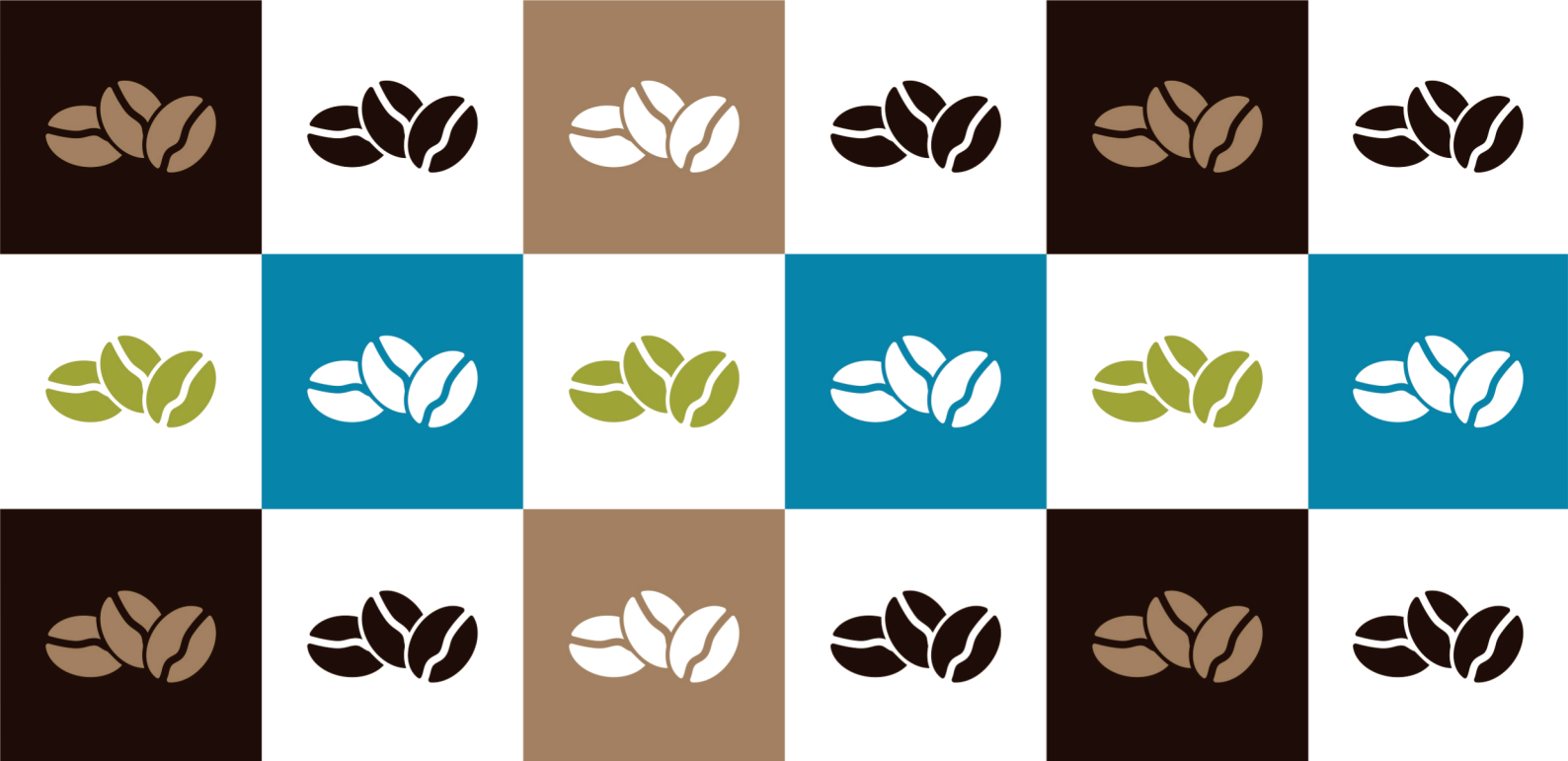




CECAFÉ PROJECT

GHG BALANCE OF CAPIXABA CONILON COFFEE

**CARBON IMPACT FROM SOIL USE CHANGE AND ADOPTION OF BEST
PRACTICES ON FARMS IN ESPÍRITO SANTO, BRAZIL.**

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ESTIMATES OF GREENHOUSE GAS EMISSIONS AND REMOVALS OF BRAZILIAN COFFEE - CECAFÉ



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ACKNOWLEDGEMENTS

We are delighted to share the results of the Carbon Balance of Conilon Coffee Production in Espírito Santo, the product of a collective regional collaboration.

We would like to extend our deepest thanks to each and every one of you for your crucial role in the success of this pioneering project.

We would also like to thank: the Espírito Santo State Department for Agriculture, Supply, Aquaculture and Fisheries (SEAG/ES) and the Capixaba Institute for Research, Technical Assistance and Rural Outreach (INCAPER) for their institutional support and their high-level technical and scientific contributions, which enabled this research to accurately convey the reality of the production practices used in Espírito Santo's conilon coffee-producing regions. Balcoffee Trading Intermediações Ltda, the Giuseppe e Pericle Lavazza Foundation, JDE Peet's, Nescafé, Sebrae-ES, Sistema OCB/ES, and Tristão Comércio Exterior, our sincere thanks for the financial aid and shared vision of sustainability, without which we would not have been able to develop this important project. Our development partners - COFCO International, the Coffee Growers Co-op of Southern Espírito Santo State (Cafesul), the Agrarian Co-op of Coffee Growers from São Gabriel (Cooabriel), Nater Coop, Nescafé, and Sucafina Brasil - we greatly appreciate and highly value their hard work and dedication in implementing the project's activities in the field. As our partners, they were fundamental in achieving the results of this work.

And we would especially like to thank the farmers and employees of the Conilon coffee farms in the state of Espírito Santo who kindly welcomed the project's technical team, shared information about their production techniques, and provided areas for soil and plant collection on their properties. Their dedication and commitment underscore the resolve of coffee growers in Espírito Santo to sustainability.

We hope that the fruits of this labour will continue to benefit not only Espírito Santo's coffee industry but also serve as inspiration for similar initiatives around the world.



SUMMARY

Analysing and calculating the sources of greenhouse gas (GHG) emissions and removals from coffee farms is necessary to assess, understand, promote and implement more sustainable practices in the field with the aim of mitigating GHG in the coffee production chain. The point of this study was to estimate the carbon footprint of Conilon coffee production in the state of Espírito Santo, Brazil, by assessing the impact of sustainable practices and changes in land use (starting from a scenario of degraded pasture) on the reduction of GHG emissions. To ensure a sufficient sample size and meet the study's objective, we selected 25 properties located in three regions of Espírito Santo, Brazil: North, the Central Serrana mountain region and South. Of these properties, 26 land use situations were sampled and grouped into pairs. The pairs were created based on similar soil physical characteristics and different coffee plantation management, one of which was traditional and the other employing good agricultural practices. The project was divided into three phases: (i) measuring the carbon stock in plant biomass and soil using destructive

sampling at the selected coffee farms; (ii) estimating greenhouse gas emissions from coffee operations, focusing on on-farm activities on these same properties; and (iii) estimating the GHG footprint. In the scenario of converting pastures to coffee farms, the study shows a balance of $-3.01 \text{ tCO}_2\text{e/ha}$ in traditional management and $-8.24 \text{ tCO}_2\text{e/ha}$ in sustainable management, which reveals that, in both types of management, coffee growers in Espírito Santo contribute to mitigating the effects of global warming, and when good agricultural practices are employed, this contribution is even greater. When the agricultural management shifts from traditional to more conservation-oriented practices, the Capixaba Conilon coffee also reveals a negative carbon balance, in the order of 1.36 tons less CO_2eq per hectare per year. This study enabled the creation of a comprehensive overview of the GHG balance for coffee production in Espírito Santo, considering both land use changes and the use of sustainable practices.



Credit: SEAG photo collection

TABLE OF CONTENTS

1.	INTRODUCTION.....	06
	PRIMARY OBJECTIVE.....	07
3.	STEP 1: GREENHOUSE GAS (GHG) EMISSIONS.....	08
	MEASUREMENTS OF CARBON SEQUESTRATION IN SOIL AND PLANT.....	16
5.	CARBON BALANCE.....	37
	CONCLUDING REMARKS.....	39
	REFERENCES.....	40
	ANNEX 1 - EMISSION FACTORS.....	43
	ANNEX 2 - PHOTOS OF PLANT AND SOIL SAMPLINGS IN THE FIELD.....	45
	ANNEX 3 - RESULT OF DENSITY ANALYSIS BY PROPERTY.....	49



INTRODUCTION

The reports of the Intergovernmental Panel on Climate Change (IPCC) point out the concerning increase in average global temperature and emphasize the urgent need to curb greenhouse gas (GHG) emissions in various sectors of the economy. These gases are primarily responsible for climate change due to their accumulation in the atmosphere and their different warming characteristics (IPCC, 2014).

Coffee farming is considered a powerful ally in the fight against global warming, given that it is a perennial crop that sequesters carbon throughout the growth cycle of the coffee shrub and stores it in the biomass for an extended period of time (Martins et al., 2015). The state of Espírito Santo in southeastern Brazil is well known for its production of Conilon coffee (*Coffea canephora* L.), both in terms of productivity and the extent of its plantations, which cover a large part of the state (INCAPER, 2014). Therefore, there is a great potential for carbon sequestration in these areas of Conilon coffee, which can be estimated by measuring the carbon stock in the biomass of the plant and, particularly, in the soil.

On the other hand, when considering the system's GHG balance, there are also the emissions caused by the different sources of emissions present in crop management practices, which include, for example,

mechanized operations, fertilization and soil correction. Therefore, employing sustainable practices is essential in reducing emissions, since the aim is to achieve production that not only sequesters the equivalent carbon it emits but also removes more atmospheric carbon than it emits in terms of GHGs, thus becoming a carbon-negative culture. Practices such as the use of organic and organomineral fertilizers with a lower nitrogen content, incorporating solar power and using pruning and coffee waste in the soil are important factors in achieving a negative GHG balance.

Armed with knowledge of the GHG balance and the key sources of emissions and removals in Conilon coffee production, Espírito Santo will be better prepared to create strategies, plans, and targets to mitigate and adapt to climate change. By taking this a step further, it will be possible to estimate the potential reduction in emissions achievable by converting degraded pastureland, which currently emits greenhouse gases, into a coffee plantation (Brunes et al., 2017).

This study focuses on quantifying the GHG balance of Conilon coffee production in traditional and sustainable management scenarios, as well as through changes in land use, so that an estimate can be reached for the overall GHG balance of Conilon coffee in the state of Espírito Santo.



PRIMARY OBJECTIVE

This study aims to estimate the greenhouse gas balance of coffee production in the state of Espírito Santo.

Primary objectives

- Estimate the emissions and removals across the different management systems to assess how the use of sustainable management affects GHG balance.
- Measure carbon stocks based on the impact caused by adopting good agricultural management practices, taking into consideration plant biomass and soil.
- Estimate the impact that coffee growing has in regard to a previous scenario of degraded pasture, using the GHG emissions balance.
- Estimate the carbon stock present in the forest areas of each property according to the phytophysiology present on site.



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STEP 1: GREENHOUSE GAS (GHG) EMISSIONS

1. Regions of Espírito Santo

The state of Espírito Santo in southeastern Brazil has emerged as one of the top Conilon coffee producing regions. The fertile land and favourable climate make it ideal for growing this variety of coffee. For decades, Conilon coffee has been very important for Espírito Santo's economy, generating jobs and boosting economic development. Conilon coffee has become more than just an agricultural crop in the state and it has now been woven into the fabric of the state's history, economy and identity. Its production continues to play a crucial role in the region's sustainable development and prosperity, ensuring the enduring legacy of the state's coffee tradition (Café, 2017; FONSECA, 2015).

As the leading state for Conilon coffee production in Brazil, Espírito Santo is characterized by its diverse terrain and different climatic environments, which enables coffee to be grown in regions at low altitudes and higher temperatures.

Coffee grows across Brazil, from north to south, with each region having its own unique features and coffee varieties; however, the Atlantic Forest biome stands out since it provides suitable conditions for coffee farming throughout the area.

The northern region of the state is known for its Conilon production and, besides being the first to grow the species, has advanced agricultural practices that use technologies to increase productivity, which greatly contributes to the development of the entire state. The southern region of the state has less land occupied by the crop but its production has grown and good agricultural practices and technologies have been implemented.

2. Characteristics of coffee production systems in Espírito Santo

2.1 Management Systems

This study considered two types of management for Conilon coffee, "Traditional" and "Sustainable". To qualify for the latter category, five

criteria were established:

1. No exposed soil in the inter-row (first years of farming)
2. Return of post-harvest waste to the soil
3. Maintenance of pruning waste in the plantation
4. Use of organic or organomineral fertilizer

In addition to management, the properties were selected in pairs, so that each pair had a different type of management but the same physical soil classification. To make it easier to estimate a consistent state-level carbon balance, this shared characteristic was used to determine the pairs, since it is directly linked to the soil's carbon storage capacity, as measured in another part of this project. Two out of the three coffee farms where soil samples were taken in the reference area of degraded pasture were classified as "Pasture" and had their emissions calculated.

Therefore, the calculation of emissions covered 25 properties, 11 with traditional management and 12 with sustainable management, which were used as the basis for the state emissions estimate of coffee production in Espírito Santo.

2.2 Crop waste management

Conilon coffee is pruned differently from other coffee species. The shrubs need to be pruned regularly in accordance with the recommended pruning schedule, which involves removing an entire stem from the coffee shrub, with the number of stems pruned every year varying. As a result, a large amount of waste is generated and, in many cases, this organic matter is used as soil cover on the plots. This accumulation of plant material will decompose and be incorporated into the soil, so the pruning waste left on the ground becomes one of the entry routes for carbon in this compartment. In addition to carbon, other nutrients are also added to the soil to make it more nutritious and healthier. At first, this practice emits GHG during its decomposition on the surface but later it becomes one of the entry points for carbon to be introduced into the soil, increasing the carbon stock in the coffee plantation's soil.

Another waste product that follows this same process is the coffee straw generated after the first stages of processing. Many producers in the state of Espírito Santo return this material to the fields as mulch.

Another option is for the coffee straw and husks to be used as fuel in the coffee bean dryers.

from the 25 Conilon coffee farms analyzed in Espírito Santo. The data was collected by the technical team of the project's partner institutions: COFCO, CAFESUL, COOABRIEL, NATER COOP and SUCAFINA. From Espírito Santo's coffee-growing regions, producers were selected from the northern zone, the central Serrana region, and the south. Notably, all these properties are situated within the Atlantic Forest biome (Figure 1).

3. Material and Methods

3.1 Data collection

Data was collected on management practices for the 2022/2023 harvest

Figura 1. Producers selected for the project



The following table shows the classification of each property, including the municipality, the coffee-growing region, the management system, the area occupied by Conilon coffee on the property and productivity per hectare.

Table 1. Property classification

ID	Municipality	Coffee region	Management	Conilon coffee area (ha)	Productivity (bag/ha/year)
11	São Gabriel da Palha	North	Traditional	6,30	77
17	Águia Branca	North	Sustainable	68,7	60
20	Águia Branca	North	Traditional	4,3	67,5
21	São Gabriel da Palha	North	Traditional	28,61	73
37	Sooretama	North	Sustainable	4	90
38	Sooretama	North	Sustainable	4	90
39	São Gabriel da Palha	North	Sustainable	4,5	79
42	São Gabriel da Palha	North	Sustainable	15,7	60
54	Itaguaçu	Central Serrana	Sustainable	20	90
55	Itarana	Central Serrana	Sustainable	8,62	80
61	Nova Venécia	North	Traditional	9,5	90
69	Barra de São Francisco/Nova Venécia	North	Traditional	21	51
73	Muqui	South	Sustainable	3,2	35
75	Muqui	South	Sustainable	7	25
76	Muqui	South	Sustainable	4	35
82	Muqui	South	Traditional	1,5	80
88	Colatina	North	Traditional	30	68,18
94	Itaguaçu	Central Serrana	Traditional	4,5	106
96	Itaguaçu	Central Serrana	Traditional	4	55
102	Itaguaçu	Central Serrana	Sustainable	5,6	83,33
103	Marilândia	North	Sustainable	13	118
111	Jerônimo Monteiro	South	Traditional	2,5	120
117	Águia Branca	North	Pasture	3,5	91,66
118	Águia Branca	North	Pasture	22	64
121	Muqui	South	Traditional	1,2	60

3.3 Method for Quantifying GHG Emissions

Greenhouse gas emissions were calculated based on the IPCC guidelines (IPCC, 2006) and the methodologies of the GHG Protocol for Agriculture and Livestock (WRI, 2013) and GHG Protocol Forests and Agroforestry (WRI, 2020), developed by the World Resources Institute in partnership with Embrapa and Unicamp. These benchmarks were used to draw up the basic calculation and GHG emission factor structure most suited to Brazilian reality.

The scope of this study focuses on emissions from the farm's production system, i.e. activities carried out within the boundaries of the farms ("pre-farm gate processes") within the Conilon coffee area.

It should be noted that carbon removals from the native forest were not taken into account when calculating the carbon balance but were reported in a separate section of this document.

The greenhouse gases (GHG) considered were carbon dioxide (CO₂); methane (CH₄) and nitrous oxide (N₂O), regulated by the Kyoto Protocol for the agricultural activity under study. In short, the calculation considered the following topics as sources of emission:

- Emissions of nitrous oxide (N₂O) and carbon dioxide (CO₂) from the use of nitrogen fertilisers in the soil.

- Emissions of CO₂ deriving from soil liming used as a corrective.
- Emissions of CO₂, CH₄ and N₂O resulting from the burning of fossil fuel.
- Emissions of CH₄ and N₂O resulting from the burning or decomposition of coffee prunings and the processing of waste (straw).
- Emissions of CH₄ and N₂O resulting from the burning of logs and coffee processing waste (husks and straw) in the dryer. Emissions of greenhouse gases from the Brazilian electricity matrix related to the use of electricity during the harvest period under study.
- GHG emissions from the production of agrochemicals used in farming (scope 3).

The conversion factor proposed by the IPCC (AR5 - 2014) was used to generate a GHG emission total for the activity. The factor measures gas emissions that are converted into carbon dioxide equivalent (CO₂e). Based on the global warming potential (GWP¹⁰⁰) proposed for each gas:

Table 2. Conversion factors

Equivalence (Co ² e)	
CO ²	1
CH 4	28
N 2 O	265

We used the following formula to estimate emissions of each greenhouse gas (GHG) from all sources. The factors used are from the aforementioned

methodological benchmarks, with reference publications cited to add local contextual adjustments.

$$\text{Emission} = \text{Activity Data} \times \text{Gas Emission Factor}$$

3.3 Assumptions about the data collected

The following criteria and assumptions were taken into consideration to align the data reported by the farmers with the calculation methodology:

- Good agricultural practices are considered to include the use of organic or organo-mineral fertilizer, maintaining pruning waste in the field, returning post-harvest waste to the soil, no exposed soil between the rows (first years

of farming).

- Plant stock: the entire vegetated area (stabilized + recovery) considered as stock.

- Coffee transport: the fuel used to transport the coffee was considered separately from on-farm fuel use; when the number of transports in the year was not informed, we considered the average ratio found between

production/number of transports; when the distance travelled was not informed, we considered the average distance from the properties (round trip); average diesel consumption used in the calculations: 0.5 L/km (consumption of 2km/L).

- only limestone was considered as an emission source; we considered 2,646 kg of urea and 2,546 kg of limestone for a property that reported in an inconsistent unit (ton).

- Soil fertilization: the manure reported by the producers was considered to be bovine manure with 1.6% N; the liquid organic matter reported by the producers for fertilization purposes was considered to have 0.002% N (Ricardo, 2016); one producer considered 9.25 t of urea and 5.15 t of synthetic fertilizer, not 925 t and 515 t, respectively (the producer has 68 ha of coffee).

- Electricity: the emission factor considered was the average provided by MCTI in 2022 and 2023, since the work takes place during the 2022/2023 harvest period.

- Pruning: only pruning carried out in the 2022/2023 harvest was considered; for the properties that did not inform the destination of the pruning, we used the destination that the majority answered (farming); pruning biomass was considered the biomass of the pruned stem according to the data generated by Professor Eduardo Cerri; number of stems per coffee shrub. 4. For coffee plantations with 4-stem pruning, 5 stems per shrub were considered; annual pruning: 1-stem pruning was considered.

- Emission factors for chemical nitrogen fertilization for organomineral fertilizers: the emission factor considered was 50% organic fertilizer, based on MAPA Regulatory Instruction 61 of July 8, 2020, which requires that organomineral fertilizers include at least 50% organic material.

- Eucalyptus moisture: the weight of a wet eucalyptus log represents 102.3% of its dry weight (da Silva Oliveira et. al, 2005).

- Allocation of straw: if the reported proportion for straw usage was inconsistent, we assumed a default distribution of 50% burned and 50% returned to the field.

- Productivity: when not informed, we used the average productivity of all the farms, resulting in 73 bag/ha/year.

Biogenic emissions: Biogenic CO₂ emissions were not taken into account, since the carbon present in this molecule comes from short carbon cycle processes and returns to its original state in a short period of time. Biogenic emissions are those that derive from residual material on the ground (prunings, bark and straw) and from combustion (firewood and biofuel). However, it is worth noting that biogenic emissions only refer to CO₂ emissions but emissions relating to other GHGs were not taken into account.

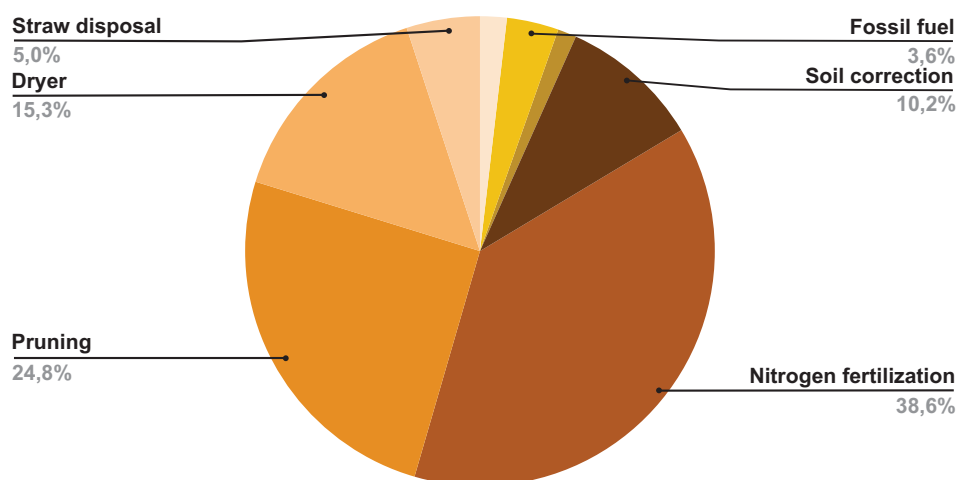
3.4 Results

3.4.1 Total emissions

The total estimates of GHG emissions quantified in the 2022/2023 harvest year ranged from 1.39 to 8.85 tCO₂e ha⁻¹ harvest⁻¹, with an overall average of 3.94 tCO₂e ha⁻¹ harvest⁻¹. The main source of emissions is nitrogen fertilization, accounting for 38.6% of emissions, followed by emissions from pruning waste (24.84%), soil correction with lime (10.19%), the dryer's energy source - burning or electricity - (15.34%), disposing of straw by burning or returning it to the field (4.98%), burning fossil fuel (3.59%), electricity consumption (1.65%), transporting coffee to the co-op (0.8%) and the production of agrochemicals (0.01%) (Figure 2).

Figure 2. Relative distribution of emission sources from the coffee farms included in the study of Conilon coffee in Espírito Santo

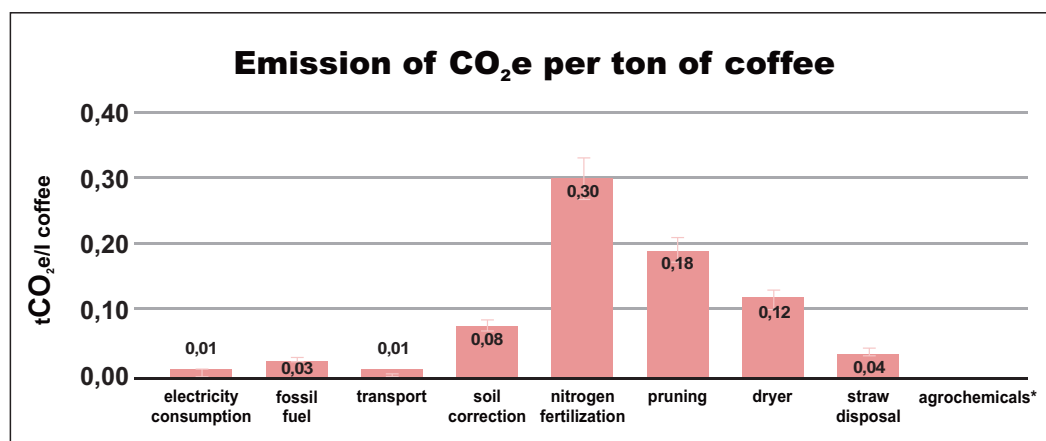
Emissions (tCO₂e) by emission source



The productivity of the 25 farms varies from 25 bags ha⁻¹ harvest⁻¹ to 120 bags ha⁻¹ harvest⁻¹. This difference may be related to the different cycles that the coffee plot is undergoing since the type of management that Conilon crop requires may cause productivity to vary greatly from one harvest to the

next. Therefore, the average yield was 73.9 bags ha⁻¹ harvest⁻¹ (considering a 60 kg bag, this number equals 4.4 t ha⁻¹ harvest⁻¹) and, therefore, the 2022/2023 harvest accounted for an average emission of 0.05 tCO₂e bag⁻¹ or 0.9 tCO₂e t coffee⁻¹.

Figure 3. Distribution of emissions by emission source and per ton of coffee produced



Source: * agrochemicals: 0.000045 tCO₂e/t coffee

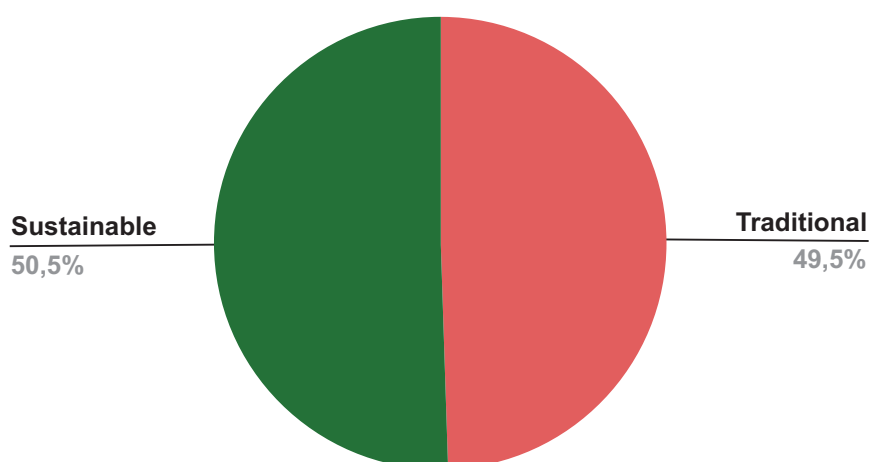
3.4.2 Comparison of emissions from management systems

Emissions per hectare from properties with traditional management vary from 1.42 to 8.83 tCO₂e ha⁻¹, reaching an average of 3.9 tCO₂e ha⁻¹. In regard to sustainable management, emissions are between 1.39 and 8.85

tCO₂e ha⁻¹, with an average of 3.98 tCO₂e ha⁻¹. These numbers may be a reflection of the short period during which sustainable practices were adopted under the "Sustainable" classification in this study and of the need for adjustments in management practices based on annual climate variations that could affect the findings within the limited inventory period. (Figure 4).

Figure 4. Average total emissions per management system

Total emissions (tCO₂e/ha)



Among the emission sources, nitrogen fertilization, pruning and drying are responsible for most of the emissions in both systems (respectively, traditional with 34.2%, 24.6% and 19.8% and sustainable with 46.9%,

22.2% and 11.1%). Figures 5 and 6 illustrate the distribution of emissions by source and by type of management employed in the coffee plantation.

Figure 5. Distribution of emissions by emission source in traditional management

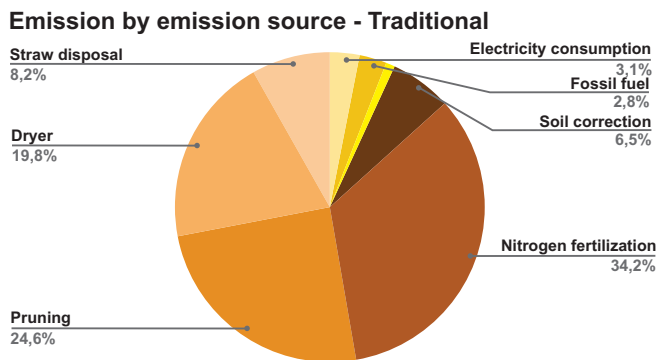
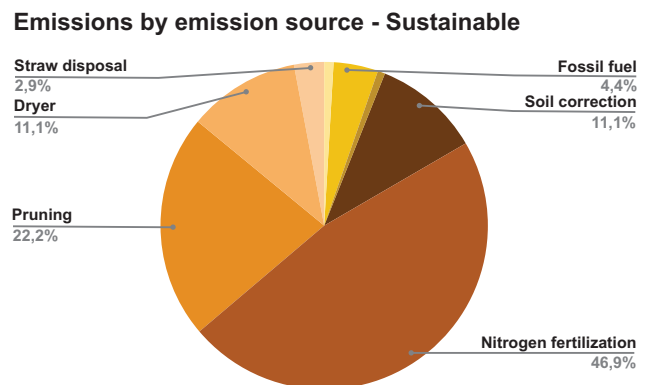


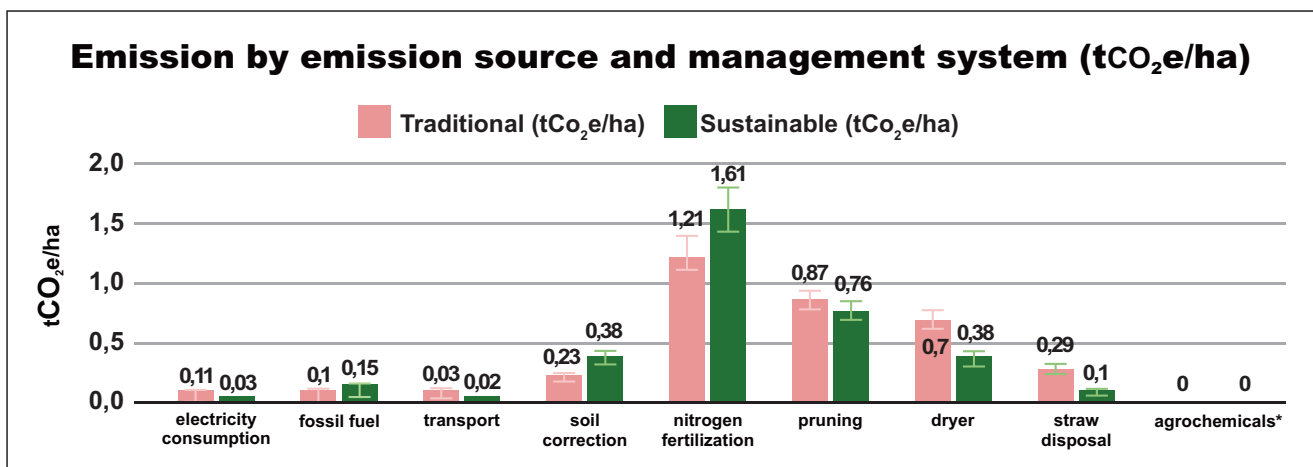
Figure 6. Distribution of emissions by emission source in sustainable management



Looking at the emission values of the most representative sources, we can see that traditional management has higher emissions than sustainable management in pruning (traditional $0.87 \text{ tCO}_2\text{e ha}^{-1}$ and sustainable $0.76 \text{ tCO}_2\text{e ha}^{-1}$) and drying (traditional $0.7 \text{ tCO}_2\text{e ha}^{-1}$ and sustainable $0.38 \text{ tCO}_2\text{e ha}^{-1}$)

$\text{tCO}_2\text{e ha}^{-1}$). On the other hand, emissions from nitrogen fertilization are higher in sustainable management ($1.61 \text{ tCO}_2\text{e ha}^{-1}$) than in traditional management ($1.21 \text{ tCO}_2\text{e ha}^{-1}$).

Figure 7. Emissions by emission source and management type ($\text{tCO}_2\text{e/ha}$)



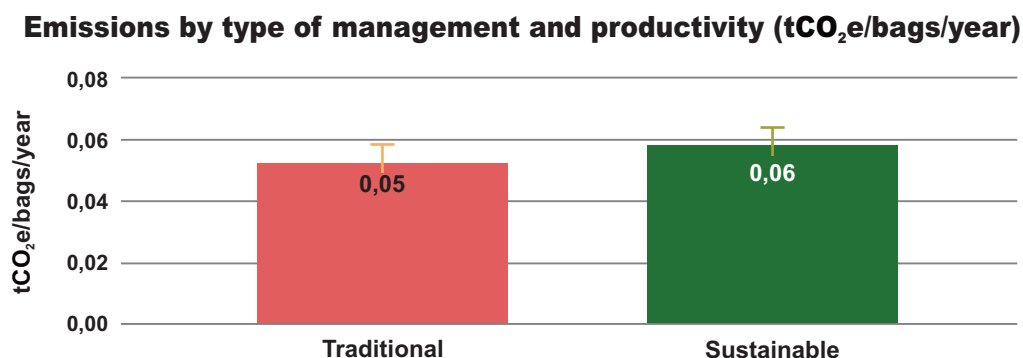
By comparing the average productivity of the properties in each management category, traditional farms emit less than sustainable ones, $0.89 \text{ tCO}_2\text{e t}^{-1}$ and $0.97 \text{ tCO}_2\text{e t}^{-1}$, respectively. These numbers in terms of bags produced during the harvest were 0.05 and $0.06 \text{ tCO}_2\text{e sc}^{-1}$,

respectively (Table 3). The following graph (Figure 8) highlights the similarity of these results. This could be because the sustainable management system was recently introduced and the farms involved are still adapting to it.

Table 3. Emission per production in different managements

Management	Emission ($\text{tCO}_2\text{e/t/year}$)	Emission ($\text{tCO}_2\text{e/bags/year}$)
Traditional	0,89	0,05
Sustainable	0,97	0,06

Figure 8. Emissions by type of management and productivity (tCO₂e/ha)



3. Carbon Stock in Vegetation

The primary and recovering permanent protection areas (PPAs) and legal reserves (LRs) and the forest surplus of each property were taken into account to calculate the carbon stock present in the vegetation of each property. It is worth noting that the size of each forest compartment varies depending on the property size, as mandated by the current Brazilian Forest Code.

All 25 properties are situated in the Atlantic Forest biome. To ensure greater accuracy, we employed the provided geographic coordinates to identify the past vegetation based on the plant physiognomy found from the geospatial layer of aboveground biomass carbon stock (AGB) by plant physiognomy in the Fourth National Communication. The carbon stocks in the above-ground biomass (AGB) present in the identified phytophysiognomies are shown in Table 4.

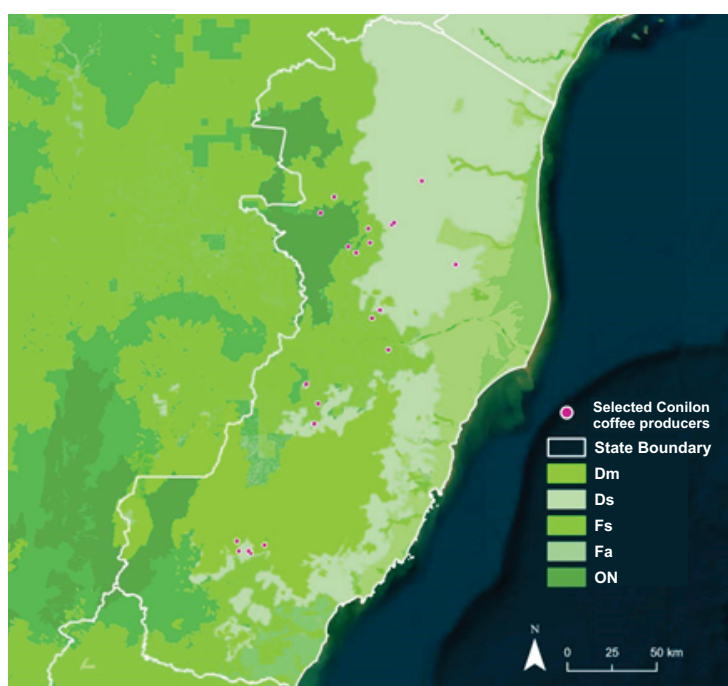
Table 4. AGB carbon stock in phytophysiognomies

Phytophysiognomy	tC/ha	tCO ₂ e/ha
Ds	141,1	517,37
Dm	140	513,33
Fs	96,5	353,83
Fa	58,05	212,85
ON	59,13	216,81

The map opposite illustrates the dispersion of properties in the different Atlantic Forest phytophysiognomies found in the state of Espírito Santo.

Figure 9. Distribution of properties in phytophysiognomies

Therefore, the total stock in the vegetation was 100,662 tCO₂e and by establishing a relationship with the coffee plantation area assessed in the project, we concluded that for every hectare of Conilon coffee there is a carbon stock in the native vegetation of 338.67 tCO₂e.





MEASUREMENTS OF CARBON SEQUESTRATION IN SOIL AND PLANT

1. INITIAL CONSIDERATIONS

Soil carbon (C) is largely responsible for the upkeep of soil quality, functionality and crop productivity, which increases global food security. As a way to mitigate greenhouse gas (GHG) emissions, soil carbon (C) sequestration has gained importance in recent decades due to its contribution to climate regulation. (Lal, 2016; Lugato et al., 2021; Beillouin et al., 2022).

One of the different options to reduce GHG emissions from planted areas is to sequester organic carbon (SOC) in the soil as a natural climate solution (also called nature-based solutions). According to Bossio et al. (2020), soil C sequestration to prevent GHG emissions in global forests, wetlands, pastures and agricultural land could reach 24 Gt CO₂eq year⁻¹, which represents 25% of the potential of natural climate solutions and comprises 47% of agriculture and pastures. However, the adoption of sustainable management practices (conservation agriculture) can determine if the agricultural soils will act as GHG sinks or as sources of GHG in the atmosphere. A few of the sustainable management practices are no-till farming, cover crops, complex crop rotations, irrigation, fertilization and organic correctives (Paustian et al. 2016; Amelung et al. 2020; Maia et al. 2022).

Brazil stands out as one of the largest food producers in the world and coffee is one of the most important agricultural crops. According to reports from the International Coffee Organization (<https://ico.org/>), Brazil leads global coffee production, followed by Vietnam and Colombia (Martinez et al.,

2024). Despite the significant social and economic importance of coffee growing in the country, research on soil carbon stocks in coffee systems remains limited, particularly when it comes to shedding light on the vast array of natural factors (climate, soil, topography, cultivation area, etc.) and types of management (species, cultivars, spacing, pruning, irrigation, use of soil correctives and fertilizers, etc.) that interfere in this process. In addition, there are even fewer studies aimed at estimating C stocks in coffee plants, given that, as a perennial crop, it has great potential for sequestering C in biomass.

As such, this study aimed to quantify how soil and plant carbon stocks are affected by two key changes in coffee-growing areas: land-use transition from pasture to coffee and the implementation of management systems based on good practices, compared to traditional practices. To achieve this goal, soil and plant samples were collected from 22 coffee-growing areas in 10 municipalities located in the state of Espírito Santo.

2. METHODOLOGY

2.1. Description of the study areas

Samplings for the subsequent quantification of soil and plant C stocks was conducted in November and December 2023. The study sites were located in the state of Espírito Santo, where different land use and management systems (traditional and good practices) were evaluated with coffee in 10 municipalities (Figure 1).



Figure 10. Geographical location of the state and municipalities where the soil and plant samples were collected.

To ensure a fair comparison within the study's parameters — evaluating the effects of land-use change (pasture to coffee) and management practices (traditional vs. good practices) — we selected groups of areas with similar soil characteristics. One of the soil characteristics used to determine these areas was soil texture since sand and clay content greatly affect soil carbon dynamics. Nine assessment "pairs" were defined with basis on the 22 areas available.

2.2. Sampling procedure and quantification of soil and plant C

The procedures adopted in this study for assessing soil and plant C follow the recommendations of the international protocols recommended by the IPCC (Intergovernmental Panel on Climate Change) and the ISO (International Organization for Standardization).

The soil sampling adopted in this study consisted of a grid made up of nine points, with a central 1 m deep trench (in which samples were collected from the 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90 and 90-100 cm) and 8 sampling points 30 cm deep (with samples collected at depths of 0–1, 10-20, 20-30 cm), 50 m apart, as shown in Figure 2. Figures 3-24 illustrate the soil and plant sampling activities and procedures in all the areas included in this study.

Figure 11. Soil sampling scheme in each assessment area, comprising 01 trench 100cm deep and 8 sampling points up to 30cm deep.

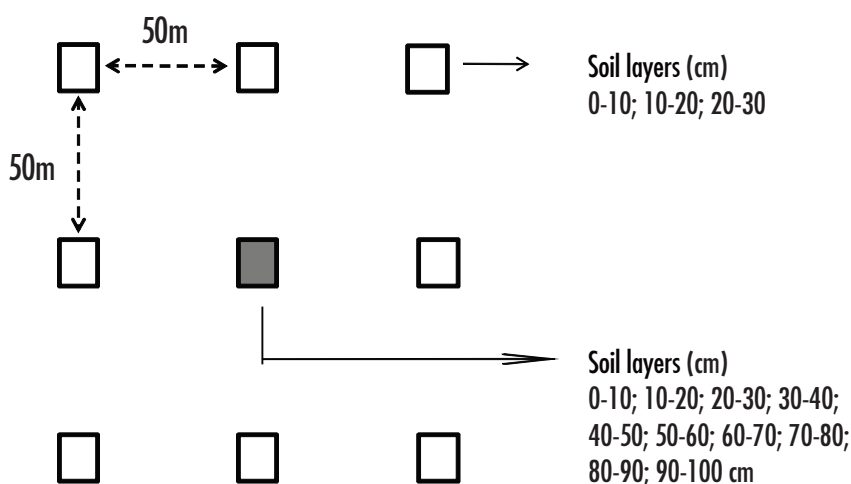


Figure 12. Soil and plant sampling process of a sampled farm



Figure 13. Soil and plant sampling process of a sampled farm



With regard to plant sampling, a sample (plant) was taken from each of the producing areas in Espírito Santo using the same technical criteria adopted by coffee growers for renewing and/or eliminating plants. For each sampled plant, the compartments of the aboveground portion and the exposed root system were analysed after extraction. The aboveground compartment was divided into branches, trunk, leaves, and litter. Similarly, the root compartment was divided into coarse and fine roots.

2.2.2. Determining soil density

To determine soil bulk density (BD), soil samples were collected using a probe equipped with a Kopeck ring of known volume. The BD was

determined in order to calculate soil C stocks (Figures 1A-9A).

2.2.3. Soil and plant C stocks

The C content (%) of the soil samples collected in the field must first be obtained to calculate the plant's soil C stocks. To do this, the total C in the soil was assessed in dry soil samples that were ground and sieved through a 100-mesh sieve (equivalent to 0.150 mm). The plant C was obtained from plant biomass sampled directly in field conditions via destructive sampling. The soil and plant C contents were determined using the dry combustion method, i.e. using a Leco elemental analyser, St. Joseph, MI, USA (Figure 14).

Figure 14. Preparation of samples collected in the field to find soil C content.



Soil C stocks (Mg ha^{-1}) were calculated by multiplying total C (%) by the BD (g cm^{-3}) and by the soil layer assessed (cm). However, different management systems can alter the BD of the soil, in which case the soil mass that represents a certain depth of soil may also vary. Therefore, comparisons of C stocks between study treatments must be carried out with equivalent soil masses, adjusting the soil depth based on a reference site (Ellert and Bettany, 1995).

It is therefore necessary to calculate a new layer for each site to represent the same soil mass in all treatments in order to correct it. The layer that represents the same soil mass is also used to accurately determine soil C stocks (Eq1).

$$\text{Equivalent layer} = (BP_{UR}/BP_{US}) \times PR \quad (\text{Eq1})$$

where: the equivalent layer is the new depth found at a specific location (cm), the BP_{UR} is the bulk density of the soil in the area under the reference management system (g cm^{-3}), the BP_{US} is the bulk density of the soil in the areas under other management systems (g cm^{-3}) and PR is the reference depth (cm).

Based on the results of the soil C stocks, the soil C accumulation rates (Eq. 2) were also calculated on the farms. The calculation described in Eq. 2 was also used to calculate the C accumulation rates of the plant.

$$\Delta C = (E_{US} - E_{UR})/T \quad (\text{Eq2})$$

where C is the soil carbon accumulation rate ($\text{Mg ha}^{-1} \text{ year}^{-1}$), E is the soil carbon stocks in the areas under the other management systems (Mg ha^{-1}),

E_{UR} is the soil carbon stocks in the reference management system (Mg ha^{-1}), and T is the time in years since the adoption of the management systems.

To calculate the plant's C stocks, the C concentration was multiplied by the corresponding dry mass of the plant. In order to quantify the plant's C stocks in hectares (1 ha^{-1}), the previously calculated C stocks were multiplied by the populations of 4000 plants ha^{-1} and 5000 plants ha^{-1} , where the final result of the plant's C stocks was the average between these two plant populations.

2.2. Statistical analysis

The final findings for soil C stocks were first subjected to the normality test, in which the existence of a central tendency (normality) of the original data was checked using the W test ($p < 0.05$), where data with a $p < 0.05$ value was considered to have a normal distribution. The homoscedasticity of the variance for the measured variables was tested with Levene's test. The independent sample t-test was used to reveal significant differences between the different management systems and for each soil layer (0-30 cm and 0-100 cm). The entire analysis was carried out using R (v.4.1.2).

3. FINDINGS AND DISCUSSION

In this first stage of assessment, in order to analyse the dynamics of soil C in the different coffee management systems, based on this section, we will evaluate soil C stocks in different coffee management systems using two approaches: i) considering the pasture area as a reference, i.e. considering the land use transition and ii) assessing the transition between management systems, in this case between the traditional management

system and good practices. Both approaches will also consider soil C stocks at different assessment depths and soil layers.

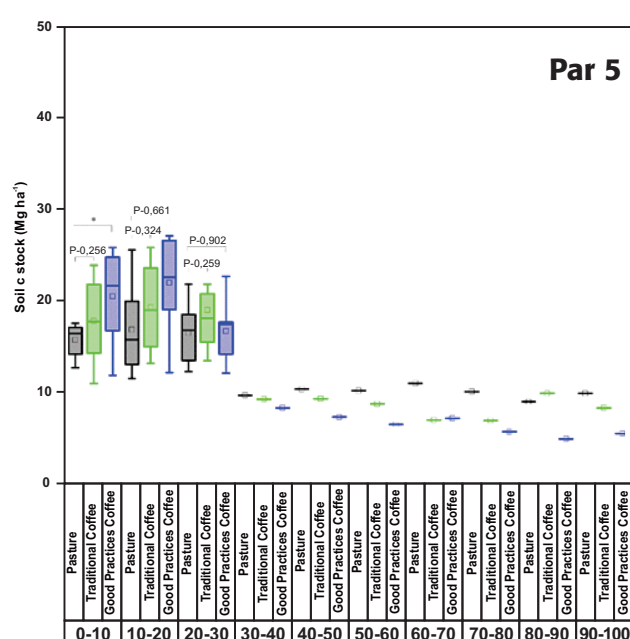
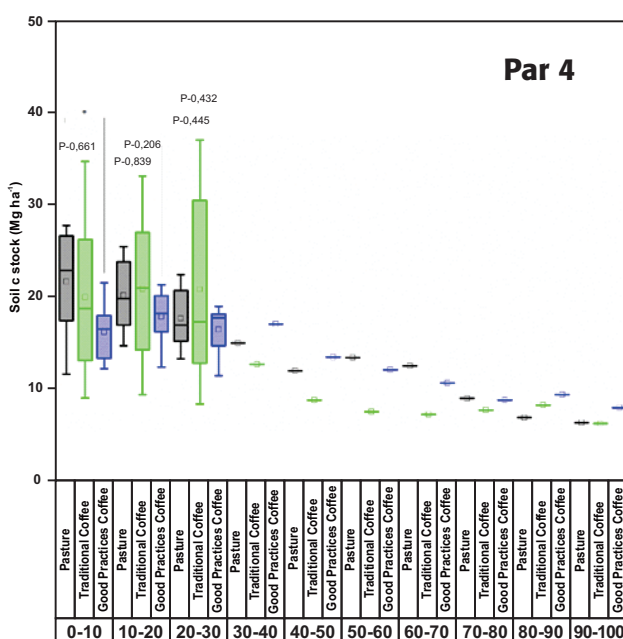
3.1. Soil C stocks at different assessment depths: pasture as the reference

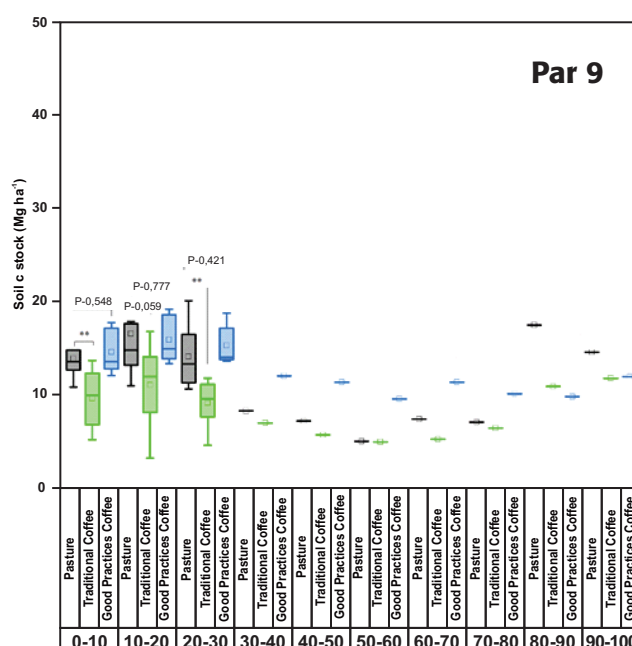
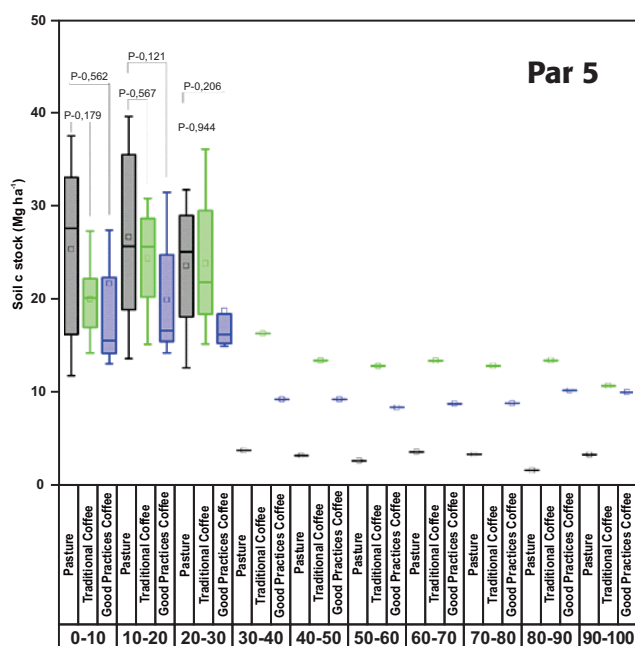
By evaluating the findings of soil C stocks according to the depth of assessment, where the pasture areas were considered as a reference (first approach), it was observed that, in general, there was a reduction in soil C stocks in the initial layers of the soil with the transition from pasture to the other coffee management systems. In the comparisons made for "Pair 1", "Pair 5", "Pair 6" and "Pair 9", the conversion from pasture to coffee under the traditional management system and good practices caused a reduction in soil C stocks of around -6% (1 Mg ha^{-1}) and -3% (1 Mg ha^{-1}) for the 10-20 cm depth, respectively, for both management systems (Figures 14). It is important to note that for the other depths, especially deeper layers, the two

coffee systems showed increases in soil C stocks compared to the pasture area. The greatest increases were seen mostly at depths of 50-60 cm and 70-80 cm, where on average they were 72% (1 Mg ha^{-1}) and 52% (1 Mg ha^{-1}) for the traditional management system and 60% (1 Mg ha^{-1}) and 38% (1 Mg ha^{-1}) for the management system based on good practices, respectively, for both depths.

Individually, it is important to point out the increase registered in "Pair 5" and "Pair 6". In "Pair 5", the greatest increases in soil C were found mainly in the 0-10 cm layer, with 13% (2 Mg ha^{-1}) for the traditional management system and 33% (5 Mg ha^{-1}) for the management system based on good practices. In turn, in "Pair 6", the greatest increases were found mainly in the 80-90 cm layer, with 620% (12 Mg ha^{-1}) for the traditional management system and 451% (9 Mg ha^{-1}) for the management system based on good practices.

Figure 14. Soil C stocks for "Pair 4", "Pair 5", "Pair 6" and "Pair 9", considering the variation in the extraction depth of the soil samples. The P value corresponds to the level of significance at each depth, with * ($P < 0.05$), ** (< 0.01) and *** (< 0.001) indicating significant differences between the pasture and coffee management systems.





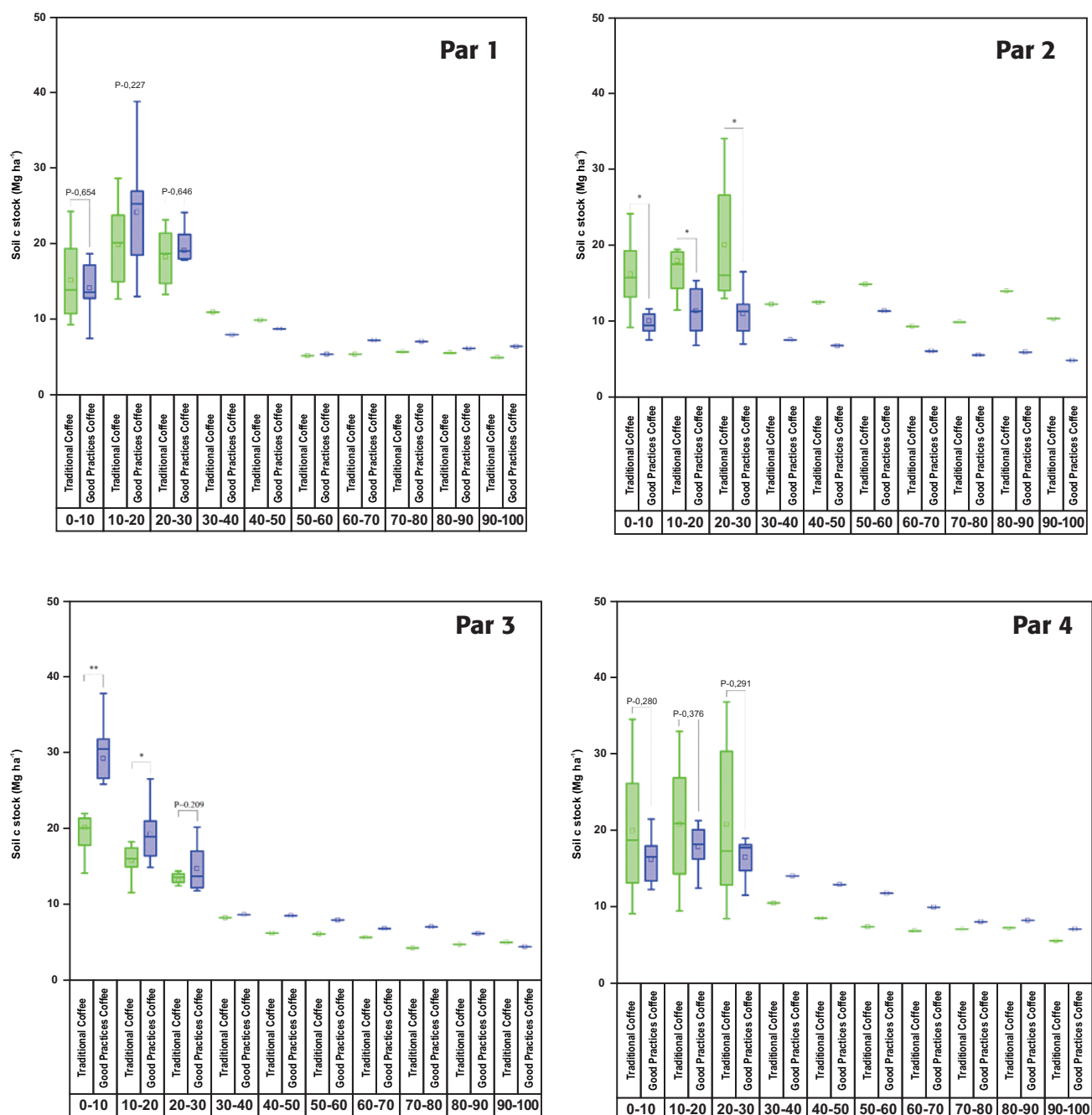
3.2. Soil C stocks at different assessment depths: traditional management system as the reference

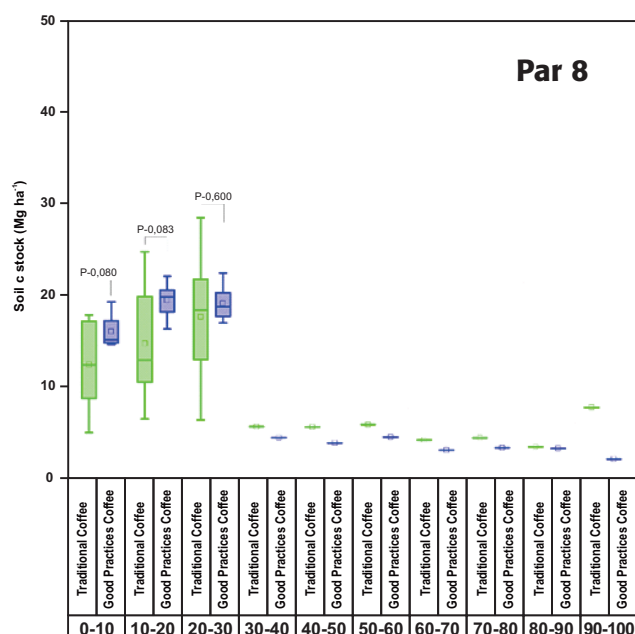
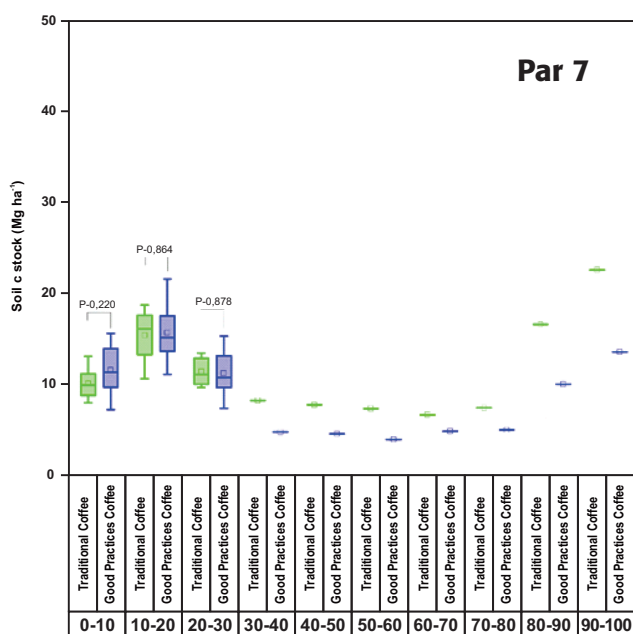
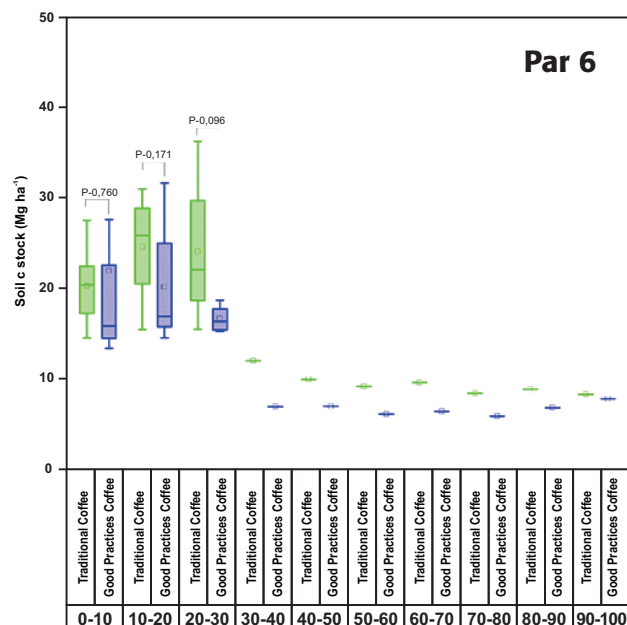
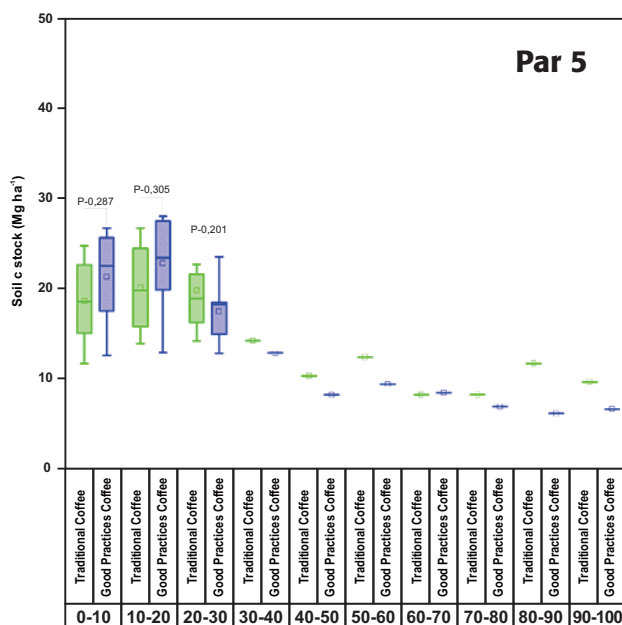
At this stage, when the traditional management system was used as a reference, it was observed that, in general, the adoption of the management system based on good practices in relation to the traditional management system led to increases in soil C stocks for most of the assessment depths (Figures 15). The greatest increases were seen at depths of 0-10 cm and 10-20 cm, with 14% (2 Mg ha⁻¹) and 8% (0.69 Mg ha⁻¹), respectively, for these depths. These findings show that the effect of using a good practices-based management system on soil C stocks occurs more in the top layers of the soil.

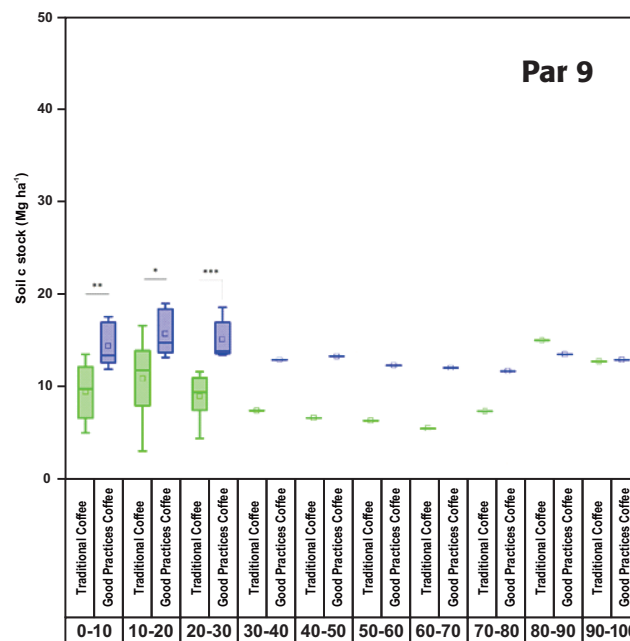
"Pair 3" shows that using the management system based on good practices as compared to the traditional management system led to increases in soil C stocks at practically all depths. The greatest increases were found mainly in the 0-10 cm, 10-20 cm and 20-30 cm layers, with 40% (9 Mg ha⁻¹), 18% (3 Mg ha⁻¹) and 15% (2 Mg ha⁻¹), respectively, for each depth.

Similarly to "Pair 3", for "Pair 5", "Pair 8" and "Pair 9" there were also increases in soil C stocks, especially at the depths of 0-10 cm and 10-20 cm with the adoption of the management system based on good practices compared to the traditional management system. For these depths, the increases were 18% (3 Mg ha⁻¹) and 14% (3 Mg ha⁻¹) in "Pair 5", 35% (5 Mg ha⁻¹) and 30% (4 Mg ha⁻¹) in "Pair 8" and 57% (6 Mg ha⁻¹) and 44% (5 Mg ha⁻¹) in "Pair 9".

Figure 15. Soil C stocks for "Pair 1", "Pair 2", "Pair 3", "Pair 4", "Pair 5", "Pair 6", "Pair 7", "Pair 8" and "Pair 9", considering the variation in the extraction depth of the soil samples. The P value corresponds to the significance level at each depth, with * ($P < 0.05$), ** (< 0.01) and *** (< 0.001) indicating significant differences between the traditional management system and the management system based on good practices.







3.3. Soil C stocks at different assessment layers: pasture as the reference

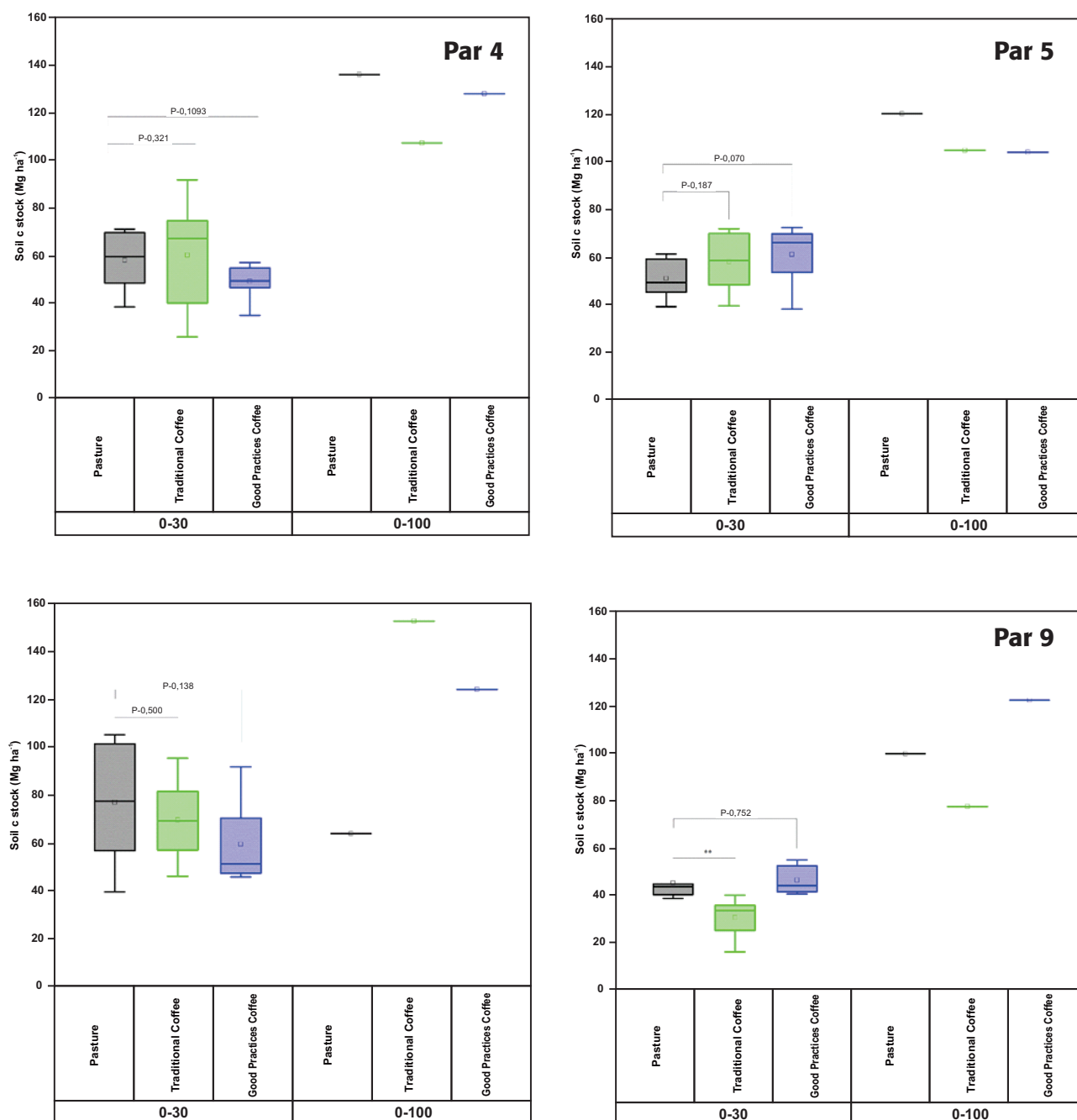
In addition to analysing the soil C stocks at each assessment depth, it is also important to check the changes in stocks in the layers from 0-30 and 0-100 cm. This stems from the fact that important international initiatives recommend assessing these layers to inventory soil C stocks due to changes in land use and management systems (e.g. IPCC, FAO, ISSO, '4 per 1000' initiative, Living Soils of the America etc).

Based on the results found when using the first approach, i.e. considering the pasture areas as a reference, it can be seen that in most cases the soil C stocks for the traditional management systems and those based on good practices exceeded the values observed in the pasture areas. In general, this effect was more pronounced when considering the 0-100 cm layer, where on average the increases for coffee under traditional management systems

and good practices-based management were 33% (6 Mg ha⁻¹) and 22% (15 Mg ha⁻¹), respectively, for both management systems (Figures 16). According to Sousa et al. (2024) grasses such as brachiaria, which are widely used in pasture areas, cause an increase in particulate C on the surface, while coffee promotes an increase in more extractable fractions in the subsurface.

It is important to note that "Pair 5" showed the greatest increases in the 0-30 cm layer for the traditional management systems and the management system based on good practices as compared to pasture, with 12% (6 Mg ha⁻¹) and 20% (10 Mg ha⁻¹), respectively, for these management systems. In addition, "Pair 6" showed representative increases in the 0-100 cm layer, of 141% (89 Mg ha⁻¹) and 95% (61 Mg ha⁻¹), respectively, for the traditional management systems and the good practices-based management system.

Figure 16. Soil C stocks for "Pair 4", "Pair 5", "Pair 6" and "Pair 9", considering the variation in the 0-30 cm and 0-100 cm layers. The P value corresponds to the level of significance in each layer, with * ($P < 0.05$), ** (< 0.01) and *** (< 0.001) indicating significant differences between the pasture and coffee management systems.



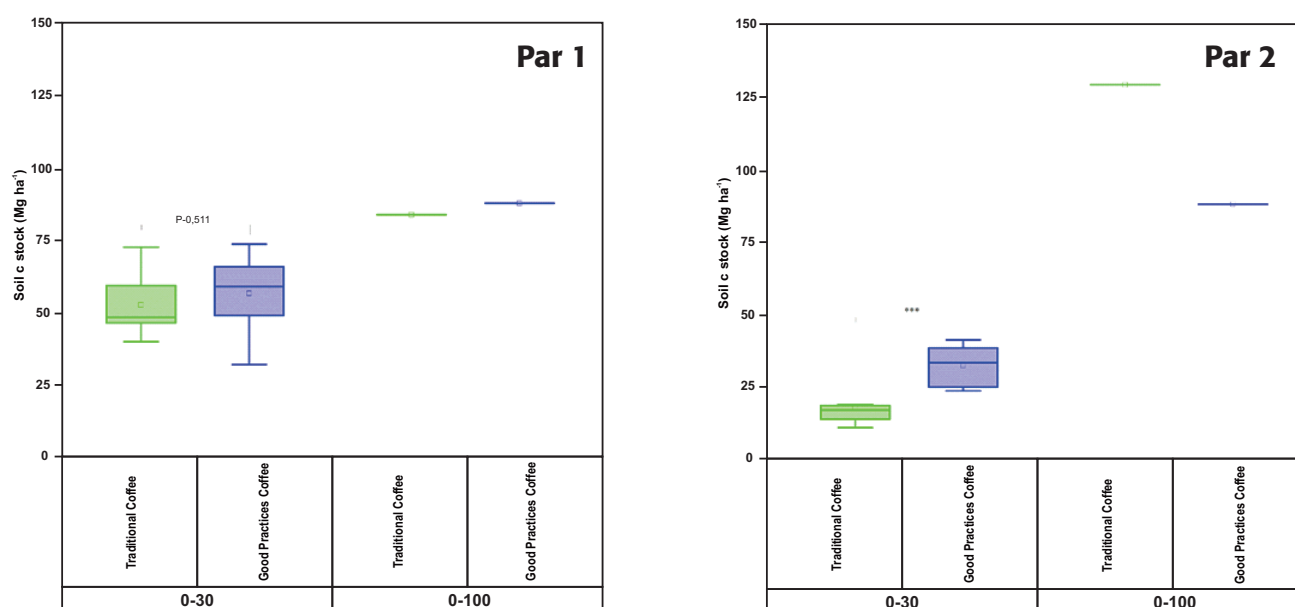
1.1. Soil C stocks at different assessment layers: traditional management system as the reference

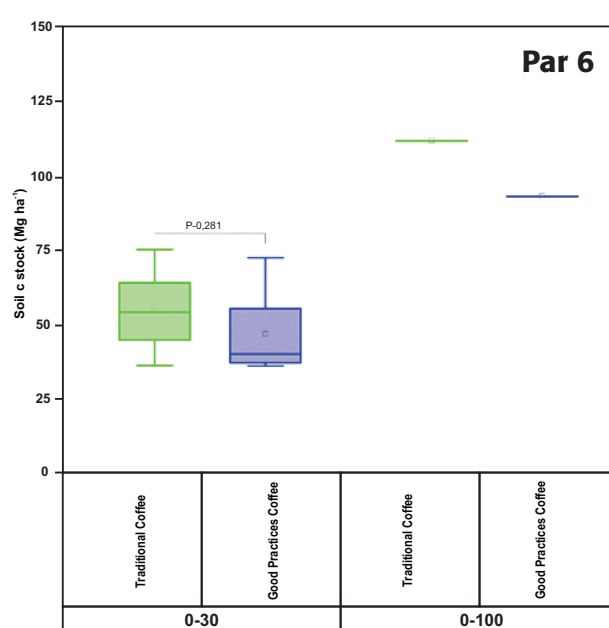
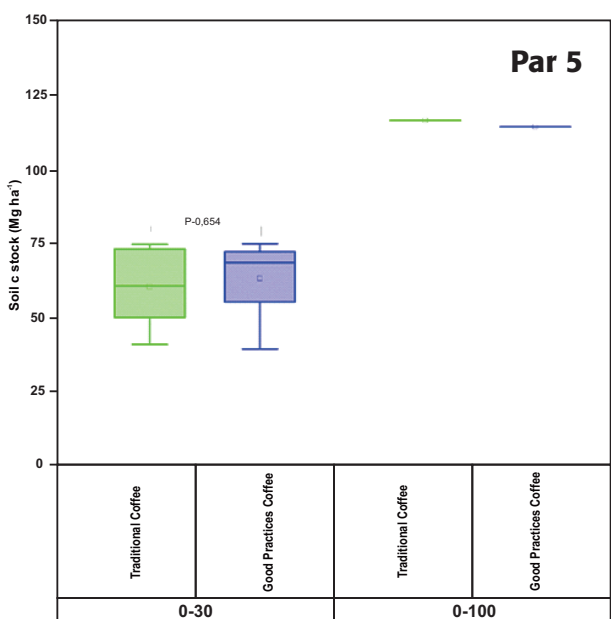
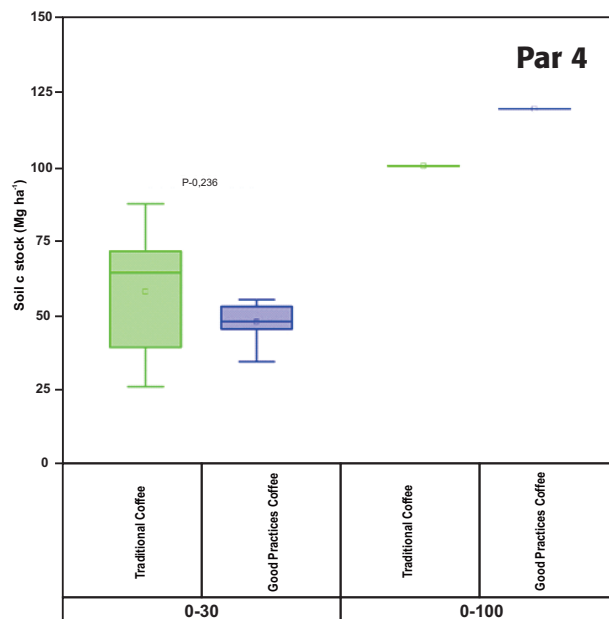
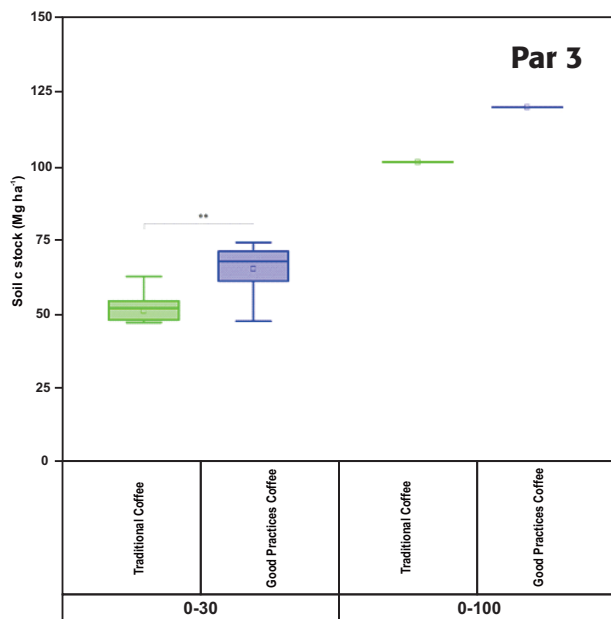
In the assessments that analysed the effect of adopting a good practices-based management system as compared with the traditional management system, it was observed that in general there was an increase in soil C stocks in both layers (Figures 17). However, the most significant increases were observed in the 0-30 cm layer, averaging 17% (5 Mg ha⁻¹). These results are in line with the study by Guimarães et al. (2014), who observed a 20%

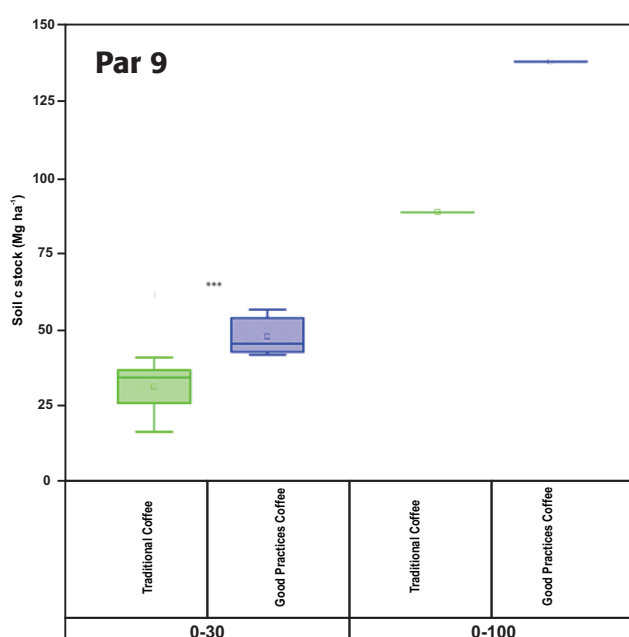
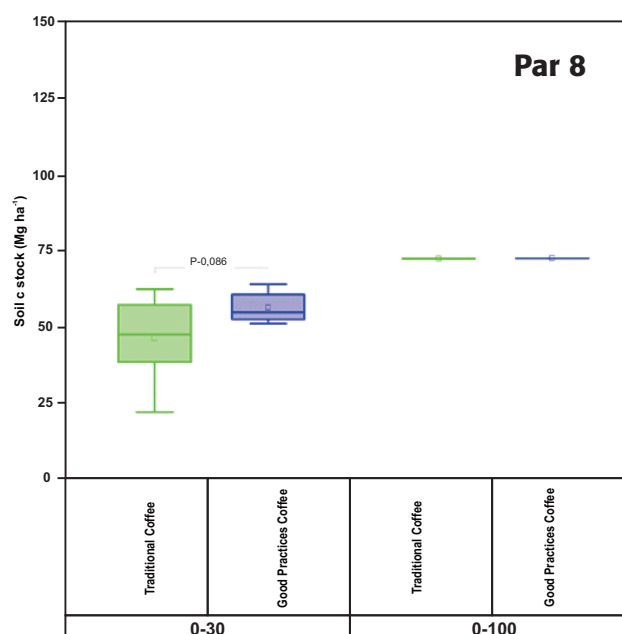
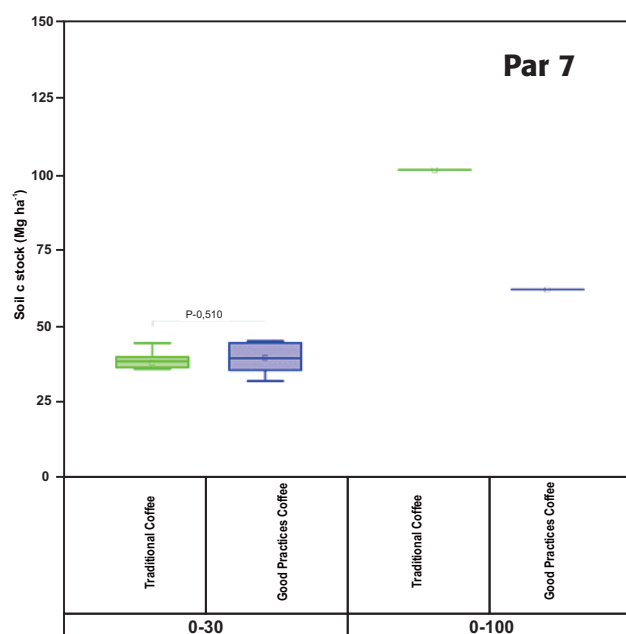
increase in soil C stock (0-20 cm) in organic coffee crops that was treated with green manure and jack beans compared to conventional crops.

Pair 1", "Pair 3", "Pair 8" and "Pair 9" showed increases in both layers assessed with the adoption of the good practices-based management system compared to the traditional management system. In the 0-30 cm layer, the increases were 7% (3 Mg ha⁻¹), 27% (14 Mg ha⁻¹), 23% (10 Mg ha⁻¹) and 56% (17 Mg ha⁻¹), respectively. In the 0-100 cm layer, the increases were 5% (4 Mg ha⁻¹), 18% (19 Mg ha⁻¹), 0.25% (0.18 Mg ha⁻¹) and 56% (49 Mg ha⁻¹), respectively.

Figure 17. Soil C stocks for "Pair 1", considering the variation in the 0-30 cm and 0-100 cm layers. The P value corresponds to the significance level in each layer, with * ($P < 0.05$), ** ($P < 0.01$) and *** ($P < 0.001$) indicating significant differences between the traditional management system and the good practices-based management system.







3.5. Plant C stocks

The C stocks of the plants were also assessed for each land use and coffee management system. Overall, the total C stocks in the coffee plants were 18% (1 Mg ha⁻¹) higher under the management system based on good practices, when compared to the C stocks found for the areas under the traditional management system (Figures 40-48). These findings reveal that the adoption of sustainable management practices in these areas has the potential to increase C stocks in coffee plants.

In addition to evaluating C stocks in coffee plants, it is also important to

highlight how carbon is being allocated to each of the main components of the plants. In this case, the branches and trunk accounted for the greatest changes in the plant's C stocks when adopting the management system based on good practices compared to the traditional management system.

As mentioned above, the branches and trunk were affected the most by the changing of the management system, but this effect differed according to the different ones assessed in this study. For "Pair 1", "Pair 3" and "Pair 5" showed the greatest effects on the trunk, where the contribution of C stocks went from 38%, 63% and 43% in the traditional management system, to 71%, 70% and 67% in the management system based on good practices,

respectively. In the case of "Pair 2", "Pair 4", "Pair 7", "Pair 8" and "Pair 9" showed the greatest effects on the branches, where the contribution of C stocks went from 12%, 9%, 10%, 7% and 12% in the traditional

management system, to 17%, 18%, 13%, 8% and 15% in the management system based on good practices, respectively.

Figure 18. Coffee plant C stocks for "Pair 1".

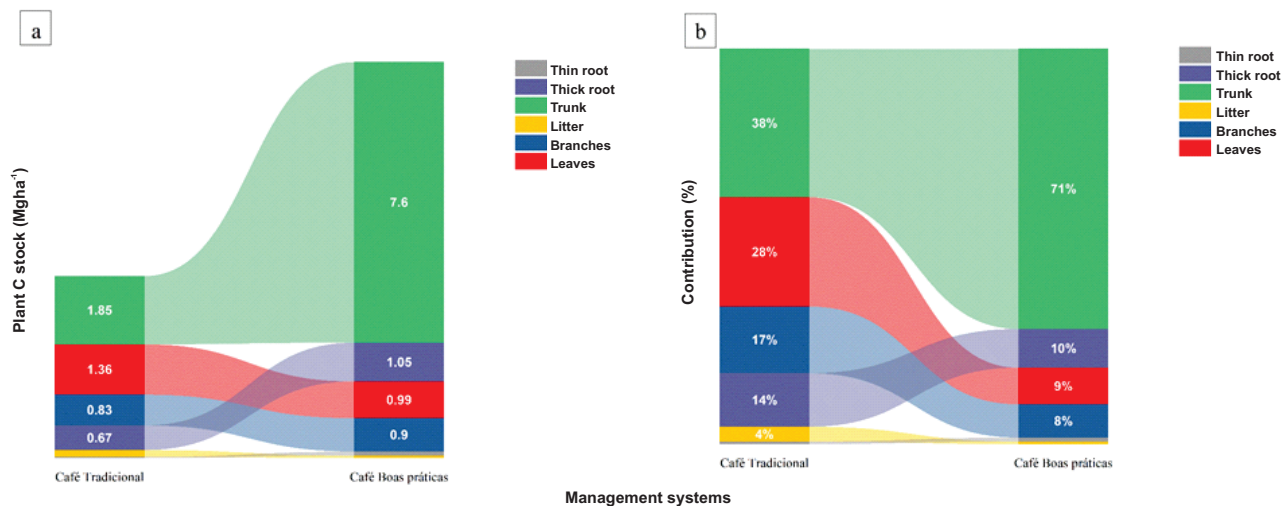


Figure 19. Coffee plant C stocks for "Pair 2".

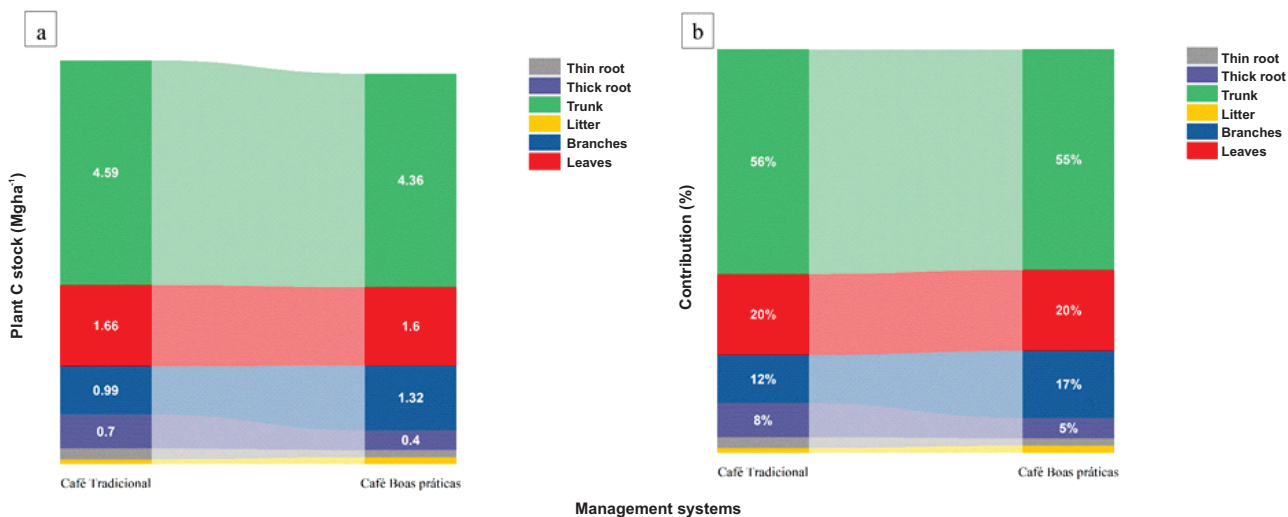


Figure 20. Coffee plant C stocks for "Pair 3".

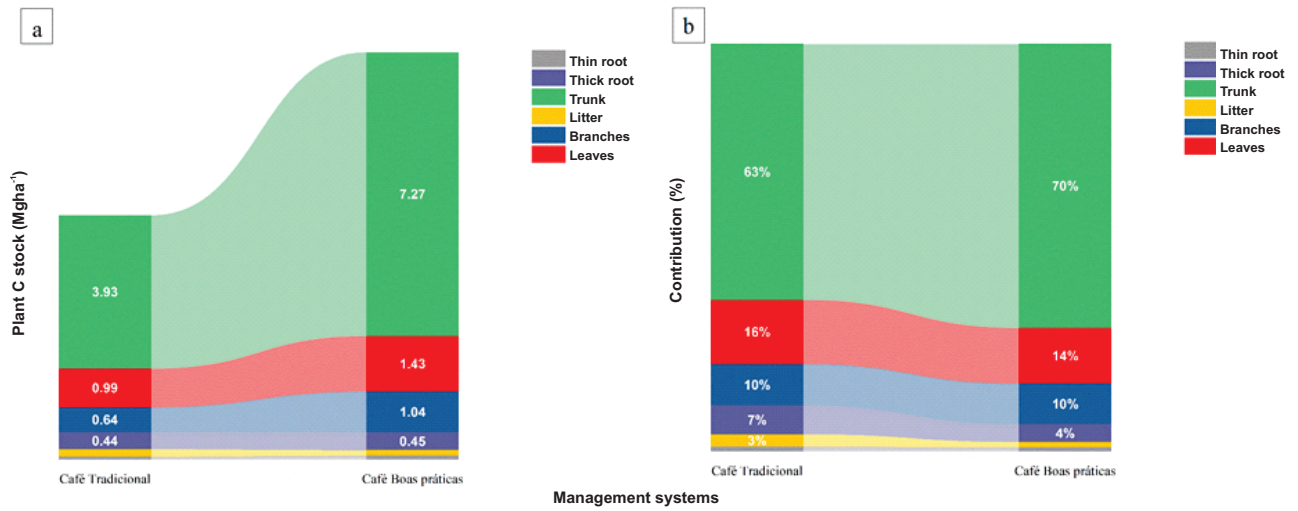


Figure 21. Coffee plant C stocks for "Pair 4".

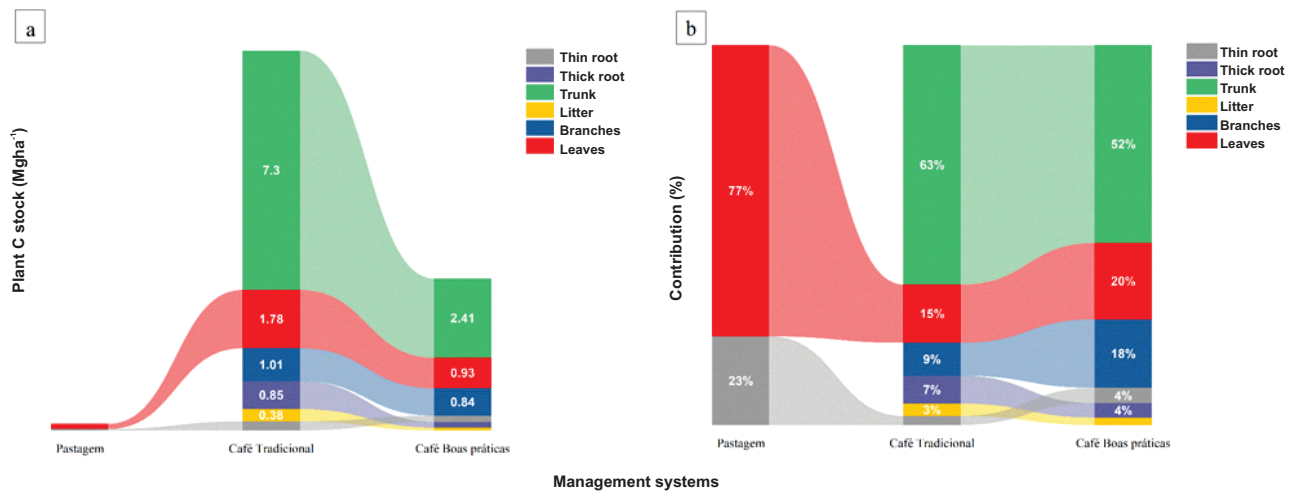


Figure 22. Coffee plant C stocks for "Pair 5".

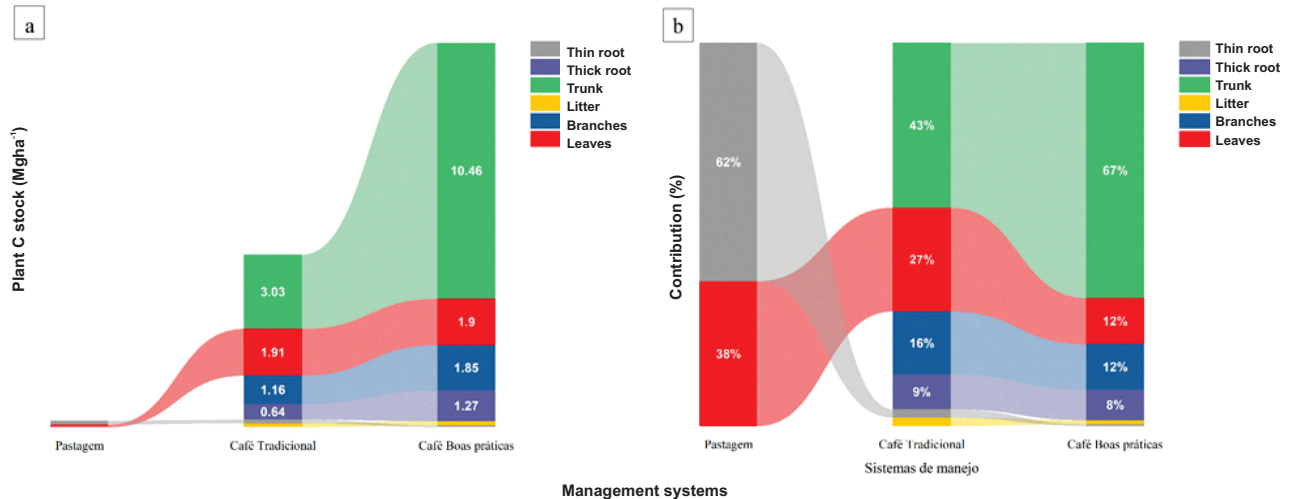


Figure 23. Coffee plant C stocks for "Pair 6".

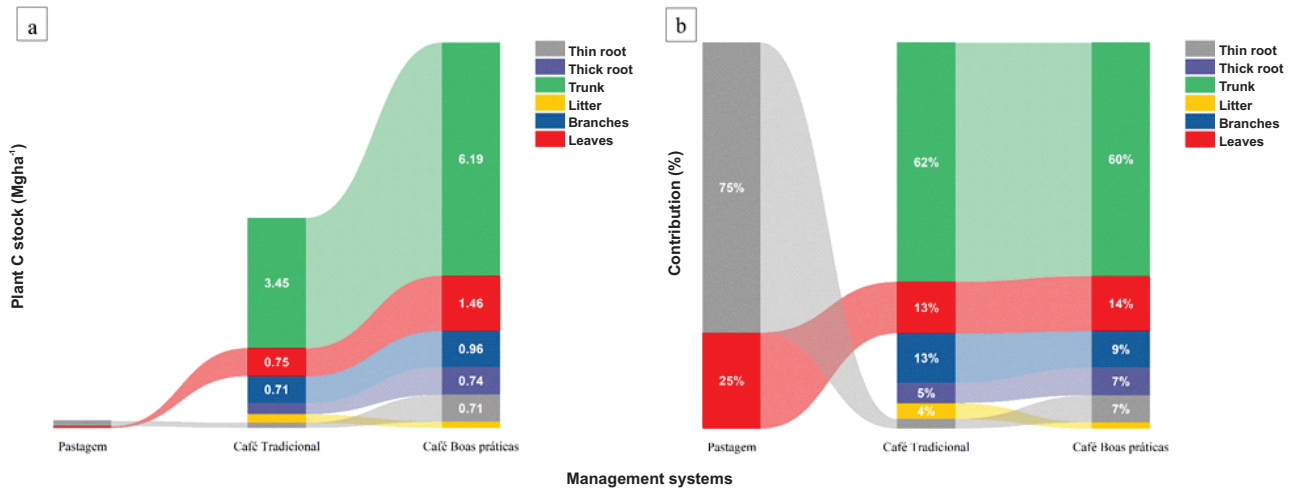


Figure 24. Coffee plant C stocks for "Pair 7".

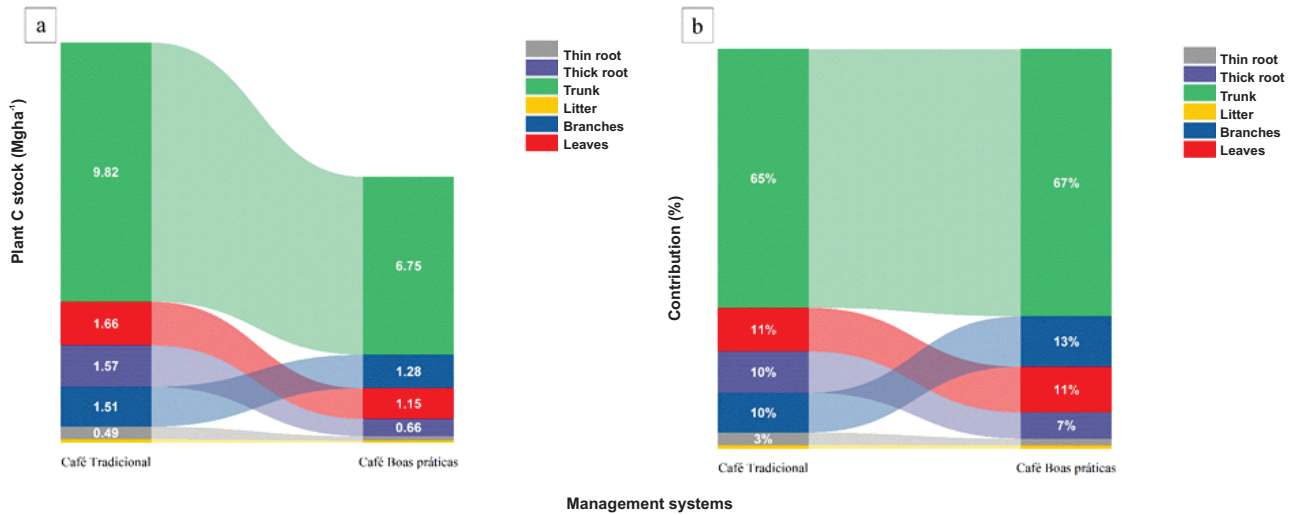


Figure 25. Coffee plant C stocks for "Pair 8".

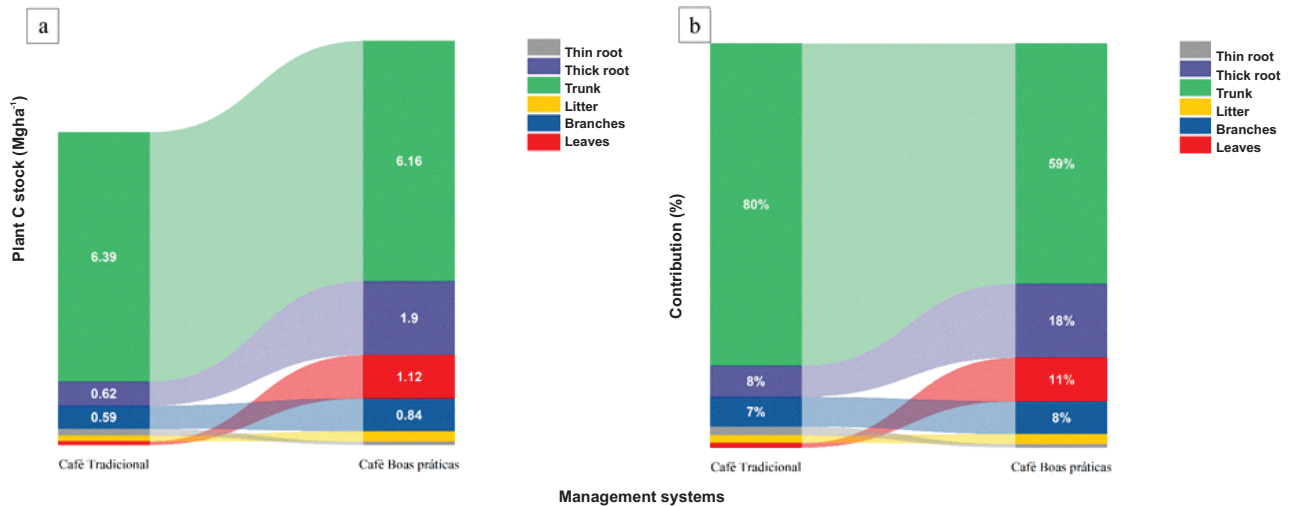
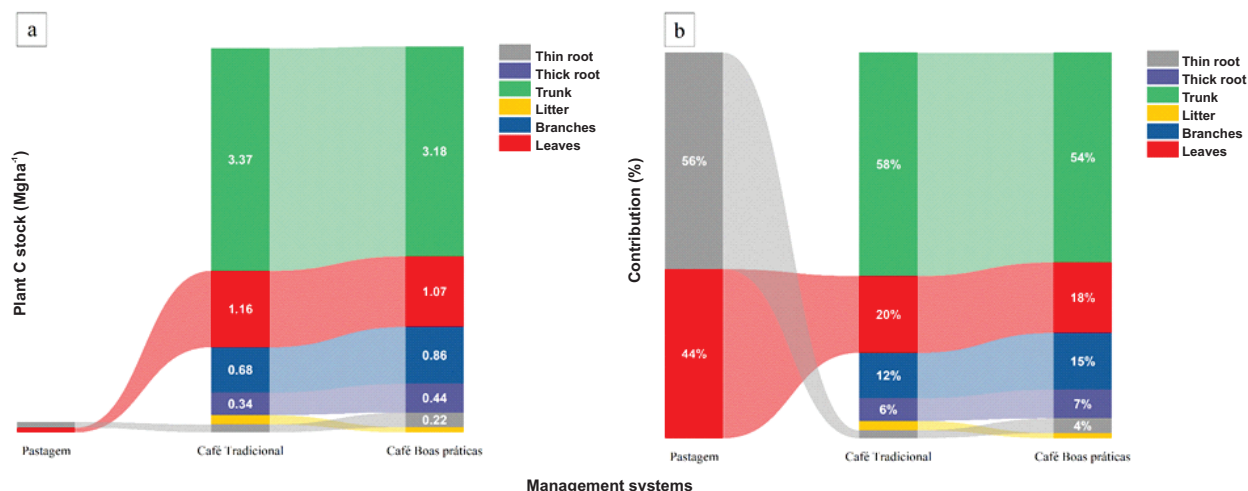


Figure 26. Coffee plant C stocks for "Pair 9".



3.6. Accumulation rate of soil C: pasture as reference

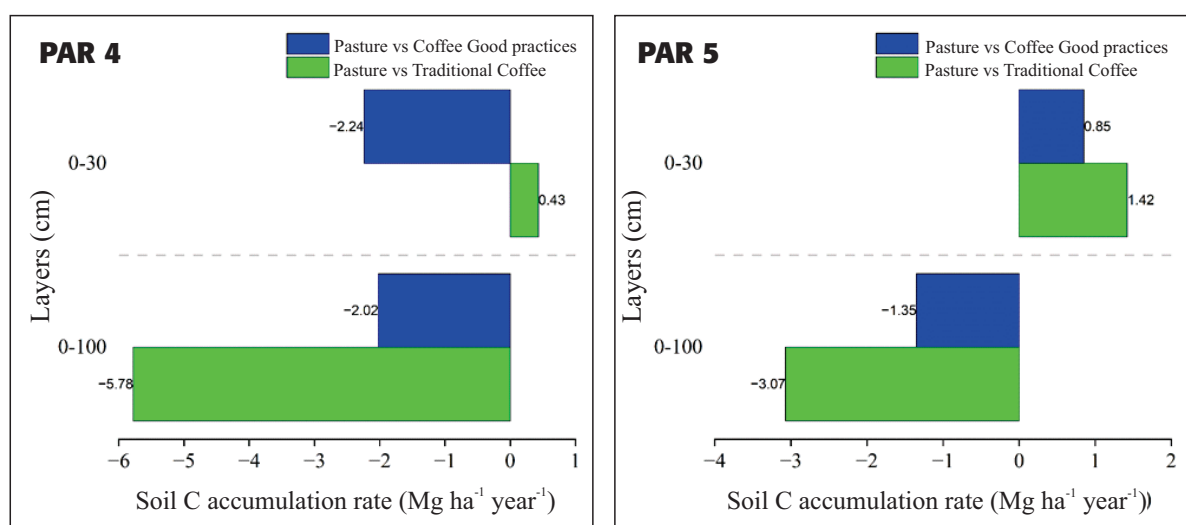
The results for the rates of accumulation of soil C, when using pasture as a reference, varied according to the reference layer.

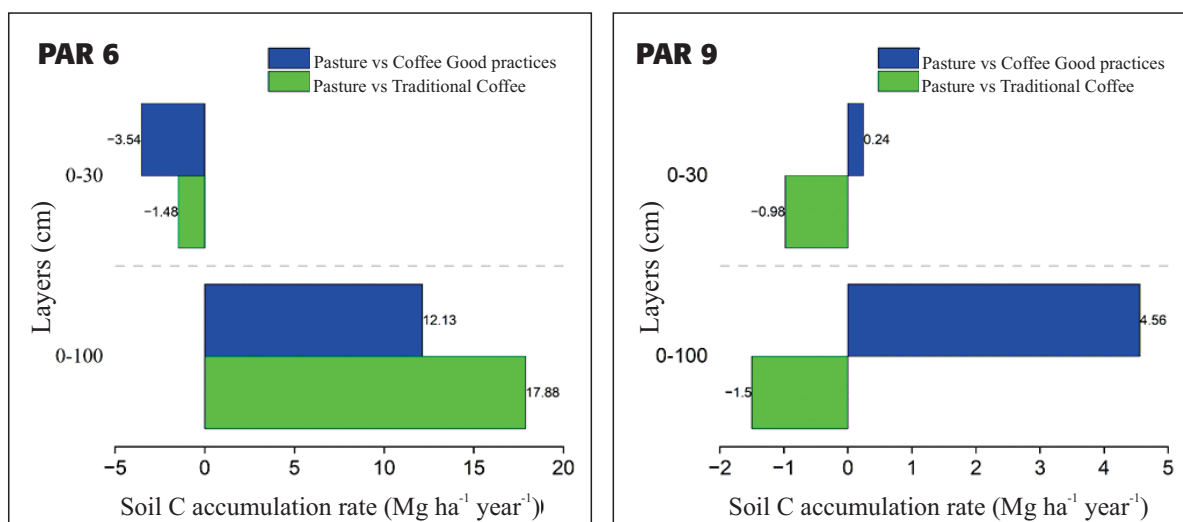
For the 0-30 cm layer, positive soil C accumulation rates were found for the traditional management system for "Pair 4" and "Pair 5", with soil C accumulation rates of 0.43 Mg h ha⁻¹ year and 1.42 Mg ha⁻¹ year,

respectively. The management system based on good practices showed positive soil C accumulation rates for "Pair 5" and "Pair 9", of 0.85 Mg ha⁻¹ year and 0.24 Mg ha⁻¹ year, respectively.

In the case of the 0-100 cm layer, positive soil C accumulation rates were found for the traditional management system for "Pair 6", with soil C accumulation rates of 17.88 Mg ha⁻¹ year. The management system based on good practices showed positive soil C accumulation rates for "Pair 6" and "Pair 9", of 12.13 Mg ha⁻¹ year and 4.56 Mg ha⁻¹ year, respectively.

Figure 27. Soil C accumulation rates due to transition from pasture to the traditional and good practices management system for "Pair 4", "Pair 5", "Pair 6" and "Pair 9".





3.7. Soil C accumulation rate: traditional management system as reference

By assessing the changes in soil C accumulation rates with the adoption of the management system based on good practices as compared with the traditional management system, it was found that in general the accumulation rates were positive, particularly in the 0-30 cm layer. For this layer, the soil C accumulation rates were 0.51 Mg ha⁻¹ year⁻¹, 1.56 Mg ha⁻¹ year⁻¹, 1.70 Mg ha⁻¹ year⁻¹, 0.34 Mg ha⁻¹ year⁻¹, 0.04 Mg ha⁻¹ year⁻¹, 0.85 Mg ha⁻¹ year⁻¹, 3.39 Mg ha⁻¹ year⁻¹ for "Pair 1", "Pair 2", "Pair 3", "Pair 5", "Pair 7", "Pair 8" and "Pair 9" (Figure 28), respectively.

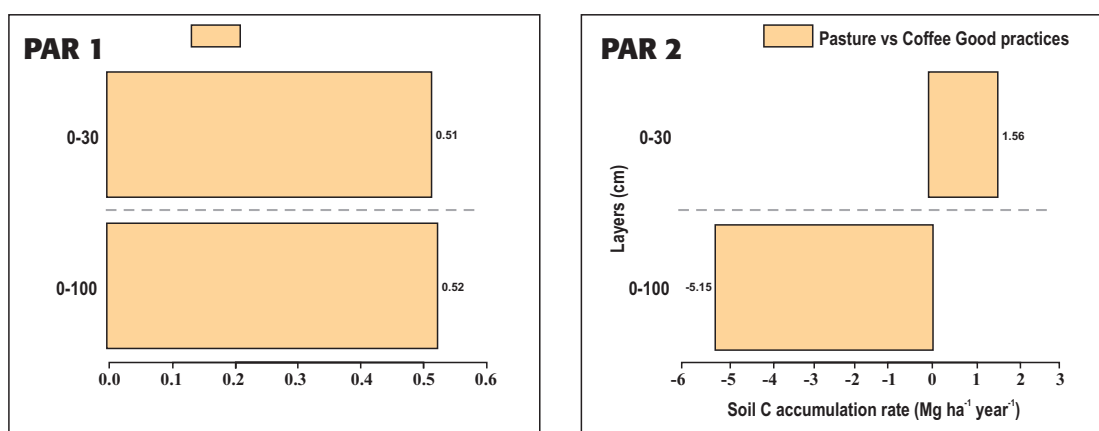
Similarly, for the 0-100 cm layer, it was observed that the adoption of the

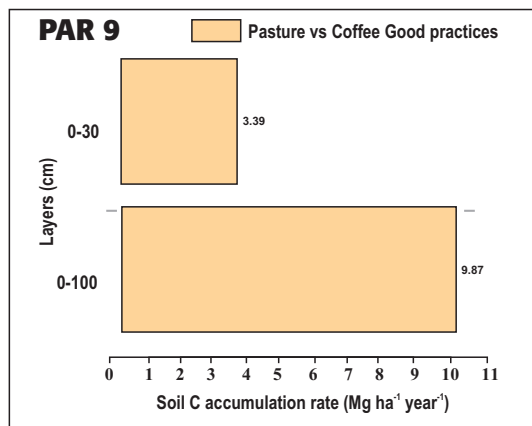
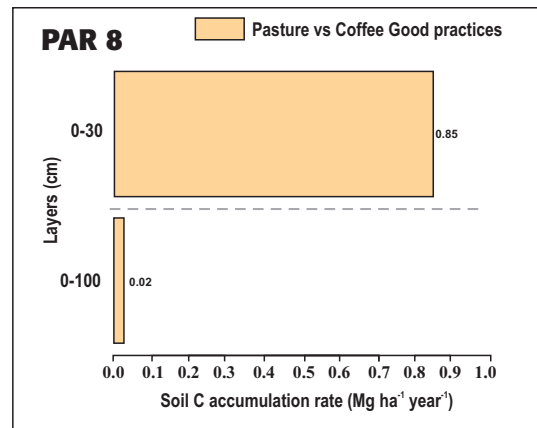
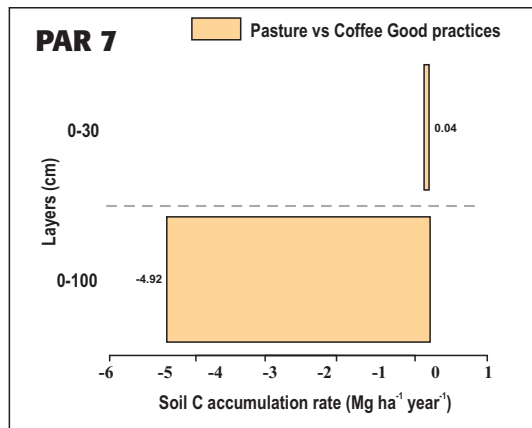
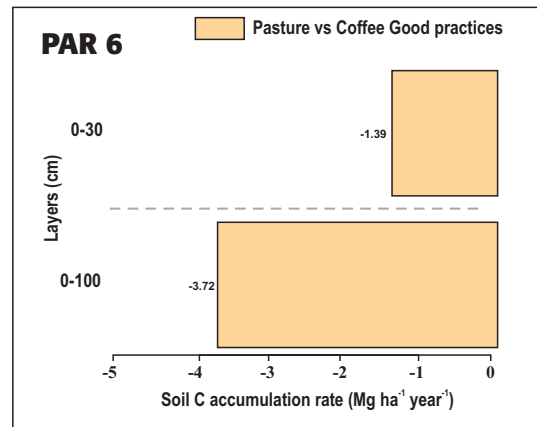
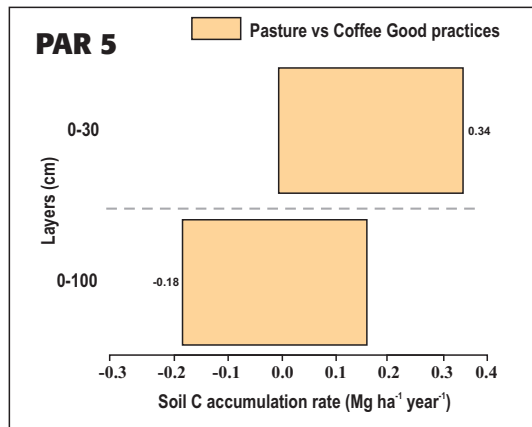
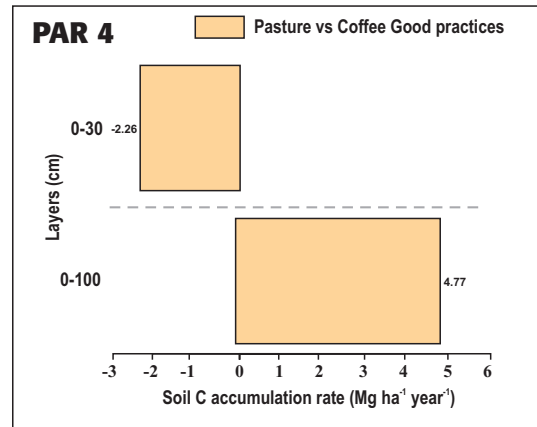
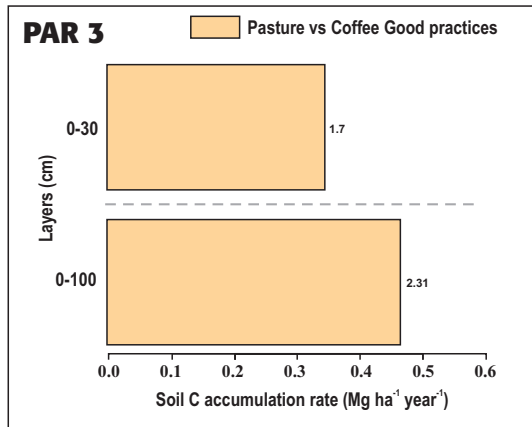
management system based on good practices as compared to the traditional management system provided positive soil C accumulation rates.

In this case, for "Pair 1", "Pair 3", "Pair 4", "Pair 8" and "Pair 9", the soil C accumulation rates were 0.52 Mg ha⁻¹ year⁻¹, 2.31 Mg ha⁻¹ year⁻¹, 4.77 Mg ha⁻¹ year⁻¹, 0.02 Mg ha⁻¹ year⁻¹ and 9.87 Mg ha⁻¹ year⁻¹, respectively.

The effect of employing a sustainable management system is corroborated by other studies in the literature. For example, in a study carried out by Belizário et al. (2018), the adoption of sustainable management practices (application of organic compost) led to increases in soil C stocks of 10%, from 58 to 63 Mg C ha⁻¹ and a soil C accumulation rate of 1.15 Mg ha⁻¹ year⁻¹.

Figure 28. Soil C accumulation rates due to transition from traditional management to good practices for "Pair 1", "Pair 2", "Pair 3", "Pair 5", "Pair 7", "Pair 8" and "Pair 9",





3.8. Plant C accumulation rates

As shown in section 3.5, the branches and trunk were the coffee plant components that accounted for the greatest changes in the C stocks of the plant with the adoption of the management system based on good practices compared to the traditional management system.

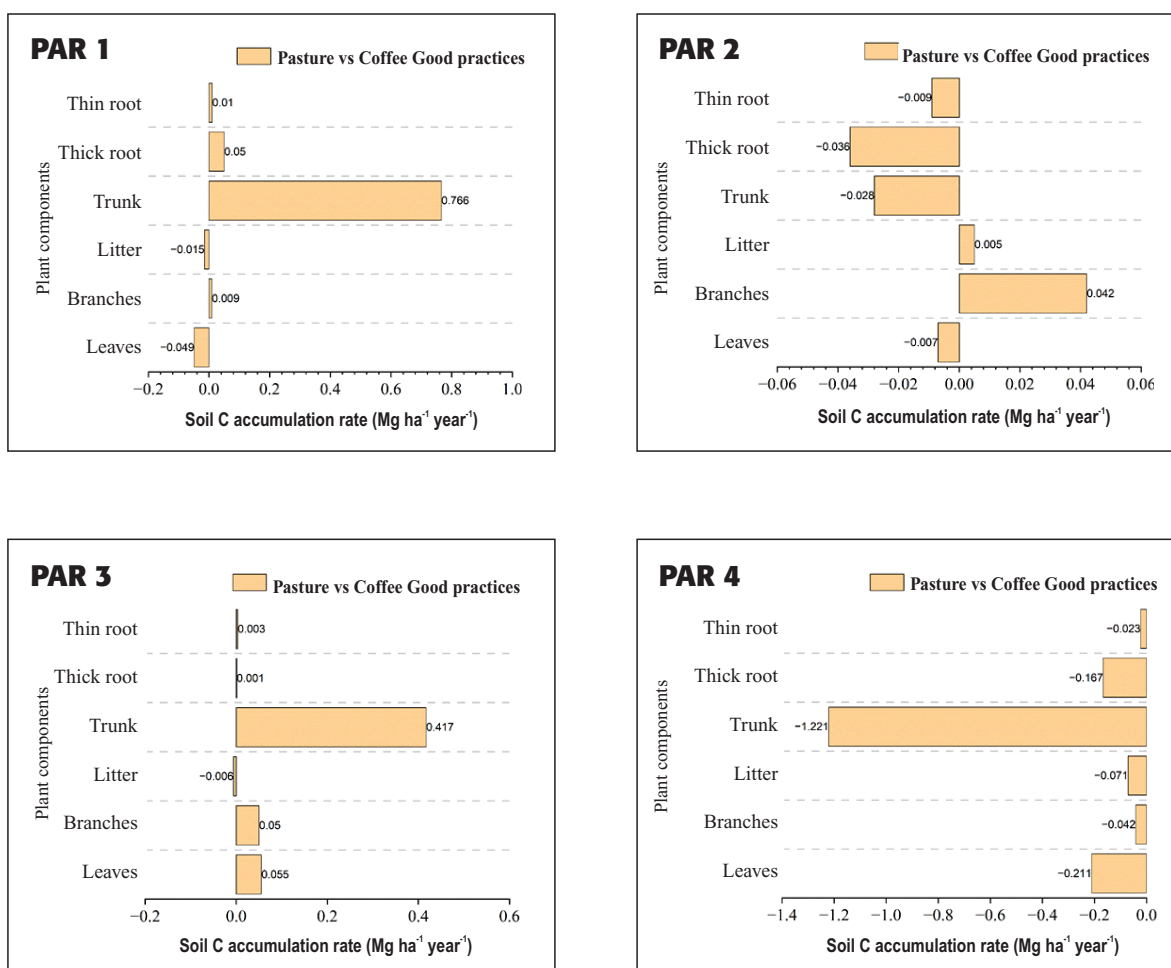
When the C accumulation rates of the plant were checked, the branches and trunk also showed the greatest changes, particularly in positive C accumulation rates.

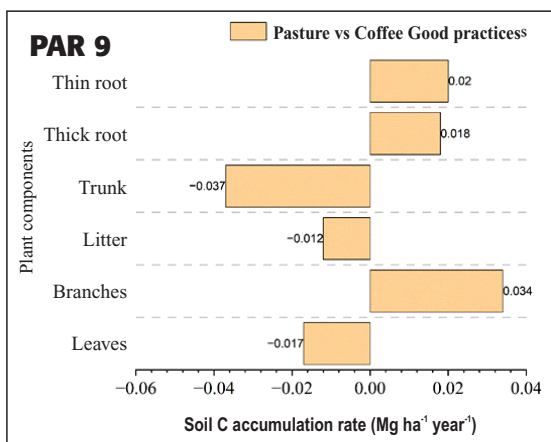
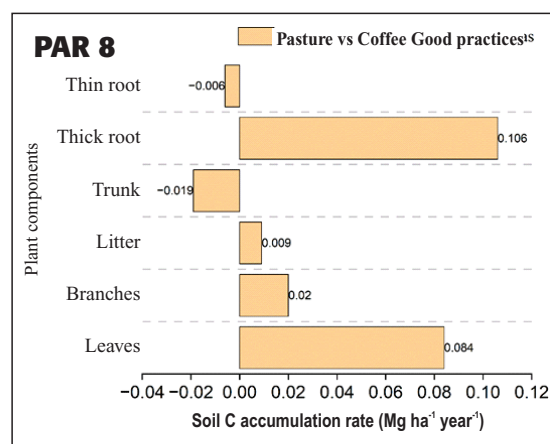
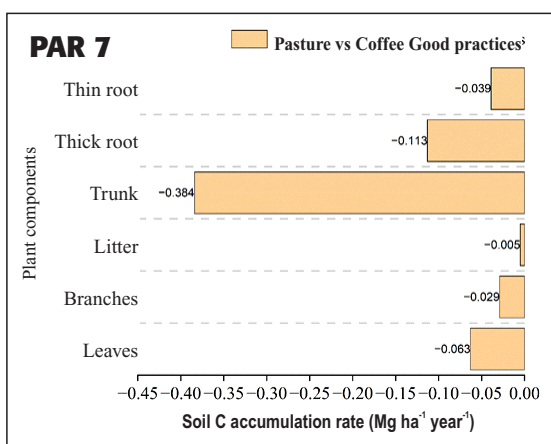
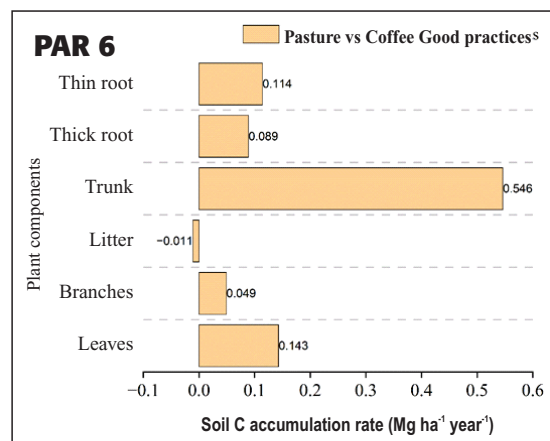
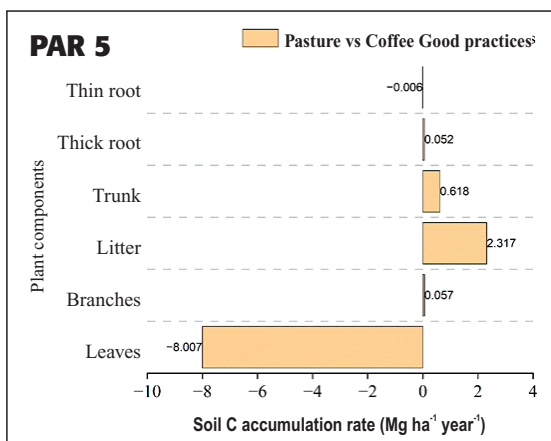
With this in mind, it should be noted that for "Pair 1", "Pair 3", "Pair 5" and

"Pair 6," the rates of C accumulation in the branches were 0.009, 0.05, 0.057 and 0.049 respectively. In regard to the trunks, the rates of C accumulation in the branches were 0.766, 0.417, 0.618 and 0.546 respectively.

It is important to quantify the carbon that is sequestered not only in the whole plant, but also in the different plant components, to understand the potential carbon stock in biomass, since few studies evaluate these assumptions. Niguse et al. (2022) found that coffee shrubs were responsible for net carbon sequestration of around 12.8% of the total carbon sequestered in agroforestry systems.

Figure 29. Plant C accumulation rates due to the transition from traditional management to good practices based management for "Pair 1", "Pair 2", "Pair 3", "Pair 4", "Pair 5", "Pair 6", "Pair 7", "Pair 8" and "Pair 9".







CARBON BALANCE

1. Methodology

The emissions balance is calculated by adding up the values of GHG emissions represented by positive values (+) and removals represented by negative values (-).

$$GHG \text{ emissions balance} = GHG \text{ emissions} + GHG \text{ removals}$$

This study has made it possible to estimate the carbon balance of coffee farming in the state of Espírito Santo in three different situations of land use change: i) from traditional management to sustainable management; ii) from pasture to traditional management and iii) from pasture to sustainable management. Only removals from soil carbon sequestration were considered in this project.

In the first situation, we estimate that the transition from traditional to

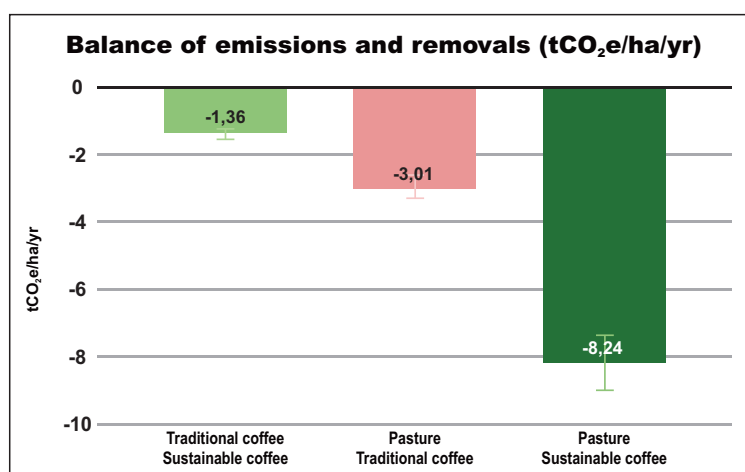
sustainable management results in a balance of $-1.36 \text{ Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, indicating a negative carbon balance and contributing to the mitigation of climate change effects. This result takes into account the emissions from the management type transition, $0.08 \text{ Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, and the sequestration of carbon in the soil of $1.44 \text{ Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$.

In terms of the GHG balance in the transition from pasture to traditional coffee growing, we took into consideration total emissions of $3.9 \text{ Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ and carbon sequestration of $6.91 \text{ Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ resulting in a balance of $-3.01 \text{ CO}_2\text{e ha}^{-1} \text{ year}^{-1}$. In the transition from pasture to sustainable management, we found a GHG balance of $-8.24 \text{ Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$, with GHG emissions of $3.98 \text{ Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$ and soil carbon sequestration of $12.22 \text{ Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$. ano e o sequestro de carbono no solo de $12,22 \text{ Mg CO}_2\text{e ha}^{-1} \text{ ano}^{-1}$.

Table 6. Carbon balance considering the different types of management

Previous management	Current management	Carbon balance ($\text{Mg CO}_2\text{e ha}^{-1} \text{ year}^{-1}$)
Traditional coffee	Sustainable coffee	- 1,36
Degraded pasture	Traditional coffee	- 3,01
Degraded pasture	Sustainable coffee	- 8,24

Figure 30. Carbon balance considering different managements and changes in land use





The carbon balance per ton of coffee produced during the year can be estimated for the two current types of management - traditional and sustainable.

These coffee plantations and their respective management systems are responsible for removing 0.71 and 1.97 Mg CO₂e t coffee⁻¹ year⁻¹ (table 7).

Table 7. Carbon balance per ton of coffee per year

Management	Mg CO ₂ e t coffee ⁻¹ year ⁻¹
Traditional	- 0,71
Sustainable	- 1,97



CONCLUDING REMARKS

Through this study, it became evident that soil C stocks were increased in both approaches: conversion from pasture to coffee and for the adoption of the good practices-based management system as compared with the traditional management system.

However, the dynamics of the increases varied according to the assessment

layer, where for conversion from pasture to coffee the effects were more significant in the 0-100 cm layer, while for the adoption of the management system based on good practices compared to the traditional management system, the effects occurred in the 0-30 cm layer (Figure 31).

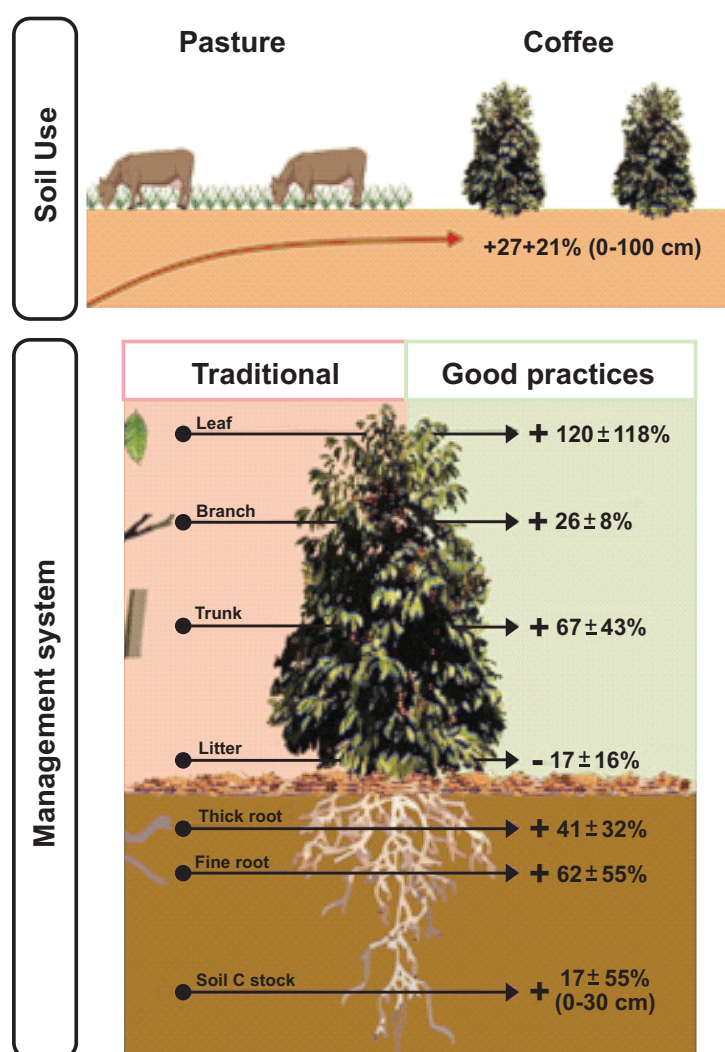


Figure 31. Effect of soil use change and soil management on soil and plant C stocks.

The C stocks in coffee plants were positively influenced by the adoption of the management system based on good practices. In this case, the greatest effects caused by the change in management system was observed in the branches and trunks (Figure 83). This shows that the effect of management also affects above- and below-ground biomass.

With regard to the GHG balance, the adoption of good agricultural practices in Conilon coffee plantations proved to be relevant in the end result, showing a more negative balance than traditional management, i.e. it contributes more to mitigating the effects of climate change.

We hope that this study will be useful for the planning of public policies that contribute to the state's economic development and prioritize the adoption of sustainable agricultural practices.



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ANNEX 1 - EMISSION FACTORS

Table 1. Emission Factors

Fertilization	Value	Unit	Source
Nitrogen Fert (ED + EI)	5,684	kg CO ₂ e/kg N	<i>Estevam et.al, 2023</i>
Dolomitic limestone	0,47667	kg CO ₂ /kg	<i>GHG Protocol 3.14.3</i>
Ureia	0,733	kg CO ₂ /kg	<i>IPCC, 2006</i>
Diesel	Value	Unit	Source
Diesel	0,002681	tCO ₂ /L	<i>GHG Protocol 3.14.3</i>
Diesel	0,00000002	tN ₂ O/L	<i>GHG Protocol 3.14.3</i>
Diesel	0,0000003	tCH ₄ /L	<i>GHG Protocol 3.14.3</i>
Diesel considered in emissions	0,87	diesel B13	-
Gasoline	Value	Unit	Source
Gasoline	0,002212	t CO ₂ /L	<i>GHG Protocol 3.14.3</i>
Gasoline considered in emissions	0,73		<i>GHG Protocol 3.14.3</i>
Energy	Value	Unit	Source
Annual average for 2022	0,0426	tCO ₂ /MWh	<i>MCTI - 2022</i>
Annual average for 2023	0,0385	tCO ₂ /MWh	<i>MCTI - 2023</i>
Average 22/23	0,04055	tCO ₂ /MWh	-
Waste	Value	Unit	Source
Waste decomposition	0,000247762	kg N ₂ O/kg produzido	<i>GHG Protocol 3.14.3</i>
Burning agricultural waste	0,0027	t CH ₄ / t resíduo	<i>IPCC, 2006</i>
Burning agricultural waste	0,00007	t N ₂ O/ t resíduo	<i>IPCC, 2006</i>
Burning - dryer	Value	Unit	Source
Burning of eucalyptus	0,0055	kg CH ₄ /kg matéria seca	<i>IPCC, 2006</i>
Burning of eucalyptus	0,0001	kg N ₂ O/matéria seca	<i>IPCC, 2006</i>



In this report, emissions related to the production of agrochemicals are considered as scope 3 since they are not under the control of the inventoried

property. The emission factors used were those found in the Ecoinvent V.3.1 database for herbicides, fungicides and pesticides.

Table 2. Emission factor considered per agrochemical used

Agrochemical used	Agrochemical considered in the emission factor
Acar./Insect/Nemat.	Pesticide
Adjuvant	Fungicide
Biological	Fungicide
Insecticide + Fungicide	Fungicide
Fungicide Insecticide/Acaricide	Pesticide
Inorganic Pest.	Fungicide
Other	Fungicide

Table 3. Emission factors - agrochemicals (Ecoinvent V.3.1)

Emission source	Emission factor (tCO ₂ e/t)
Herbicide	0,01808
Fungicide	0,01898
Pesticide	0,01724



ANNEX 2 - PHOTOS OF PLANT AND SOIL SAMPLINGS IN THE FIELD

Soil assessments



Plant assessments





Soil assessments

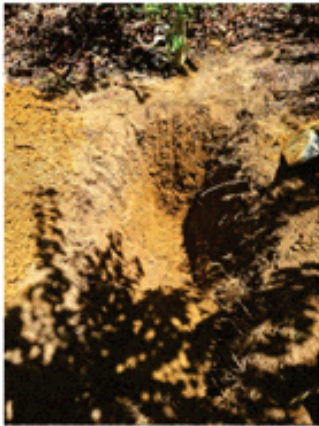


Plant assessments





Soil assessments

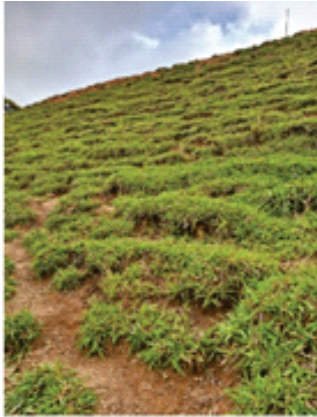


Plant assessments





Soil assessments



Plant assessments





ANNEX 3 - RESULT OF DENSITY ANALYSIS BY PROPERTY

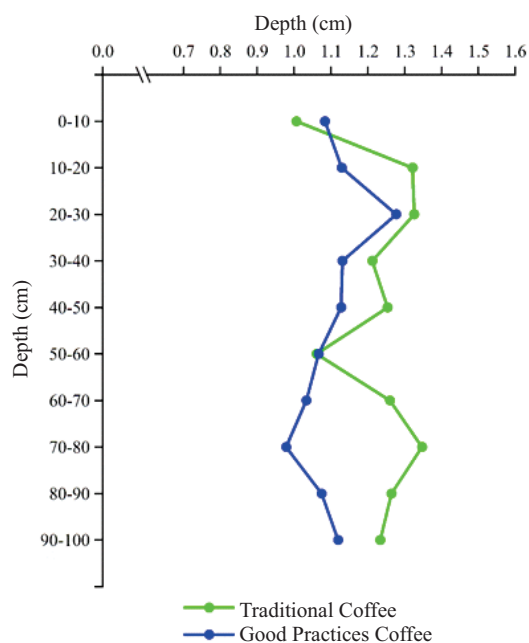


Figure 1A. DP values for "Pair 1", considering the variation in the extraction depth of the soil samples.

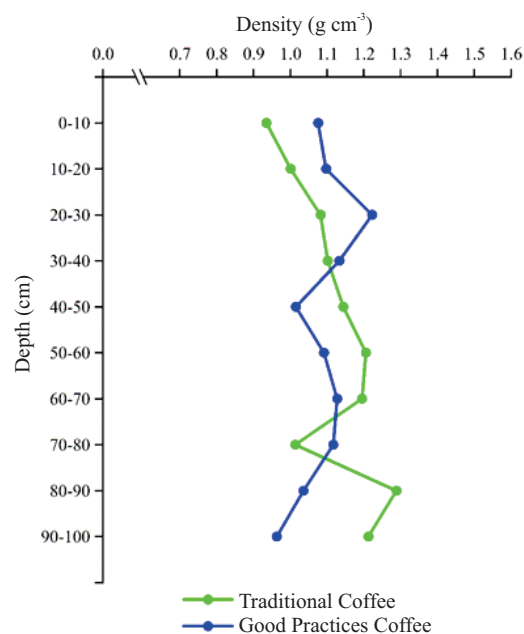


Figure 2A. DP values for "Pair 2", considering the variation in the extraction depth of the soil samples.

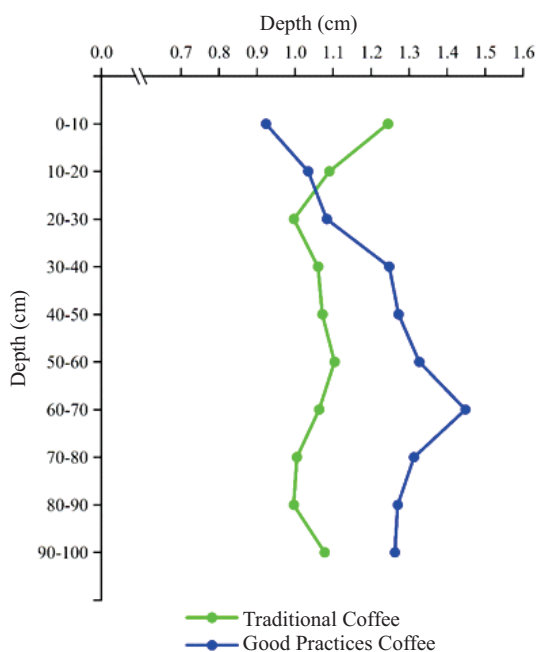


Figure 3A. DP values for "Pair 3", considering the variation in the extraction depth of the soil samples.

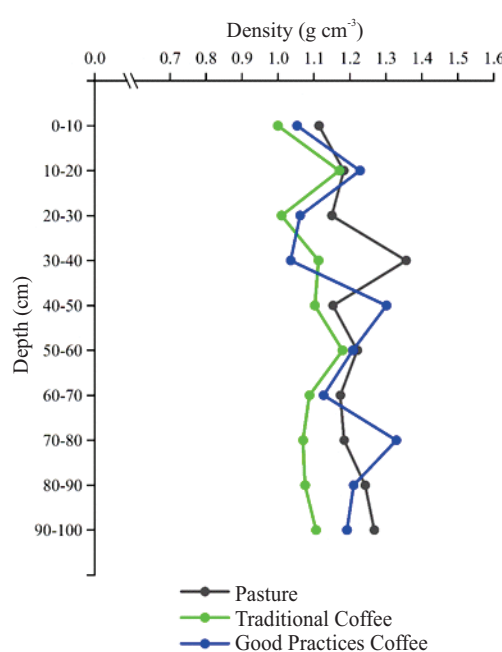


Figure 4A. DP values for "Pair 4", considering the variation in the extraction depth of the soil samples.

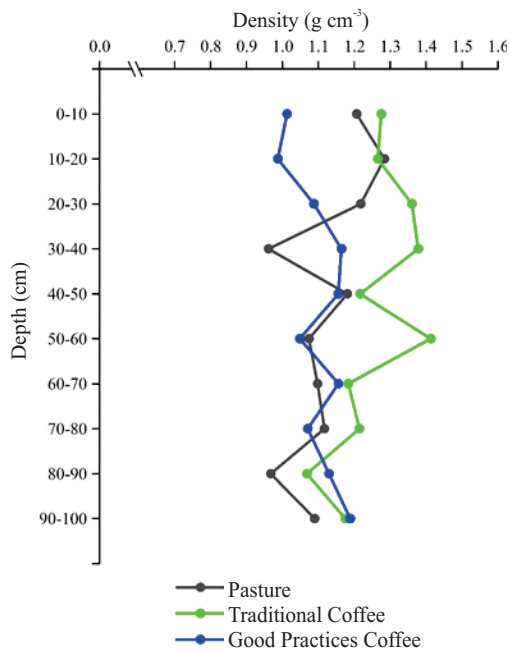


Figure 5A. DP values for "Pair 5", considering the variation in the extraction depth of the soil samples.

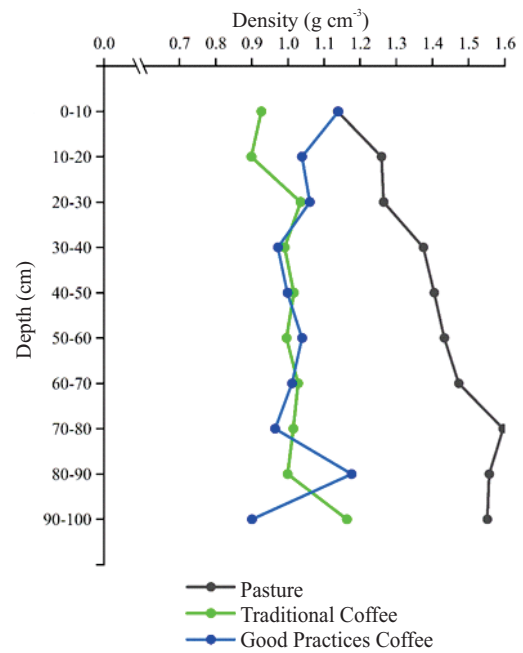


Figure 6A. DP values for "Pair 6", considering the variation in the extraction depth of the soil samples.

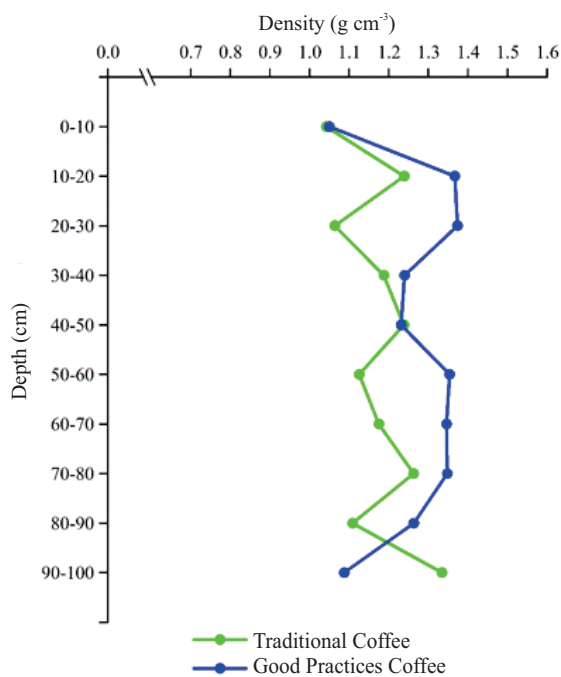


Figure 7A. DP values for "Pair 7", considering the variation in the extraction depth of the soil samples.

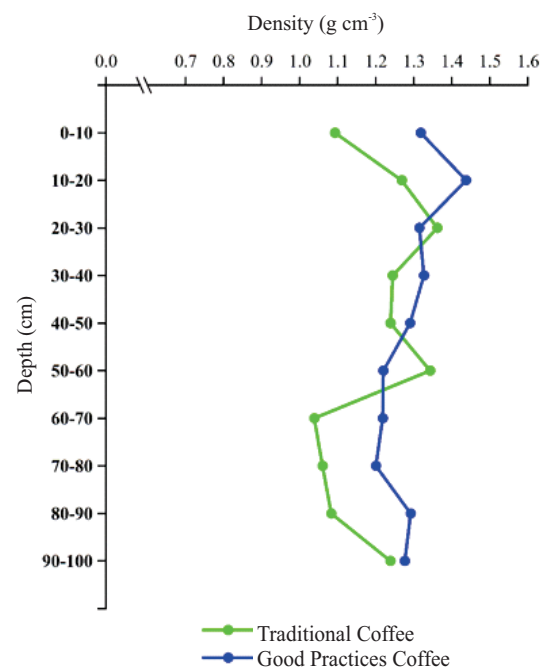


Figure 8A. DP values for "Pair 8", considering the variation in the extraction depth of the soil samples.

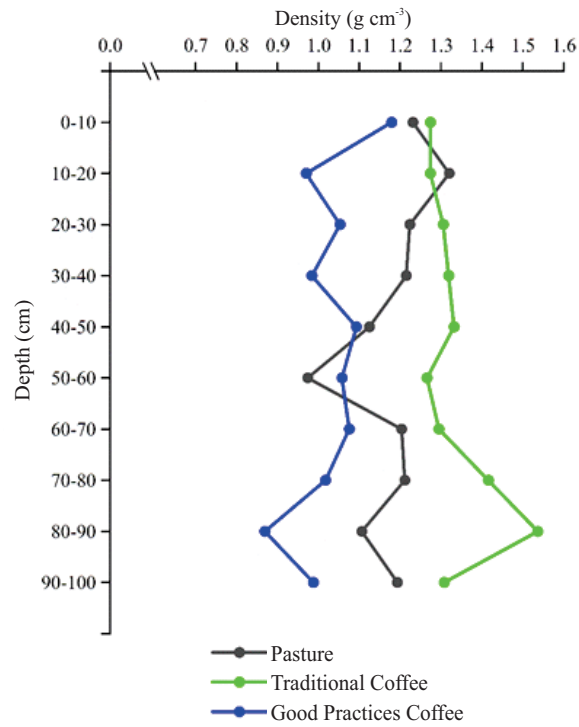
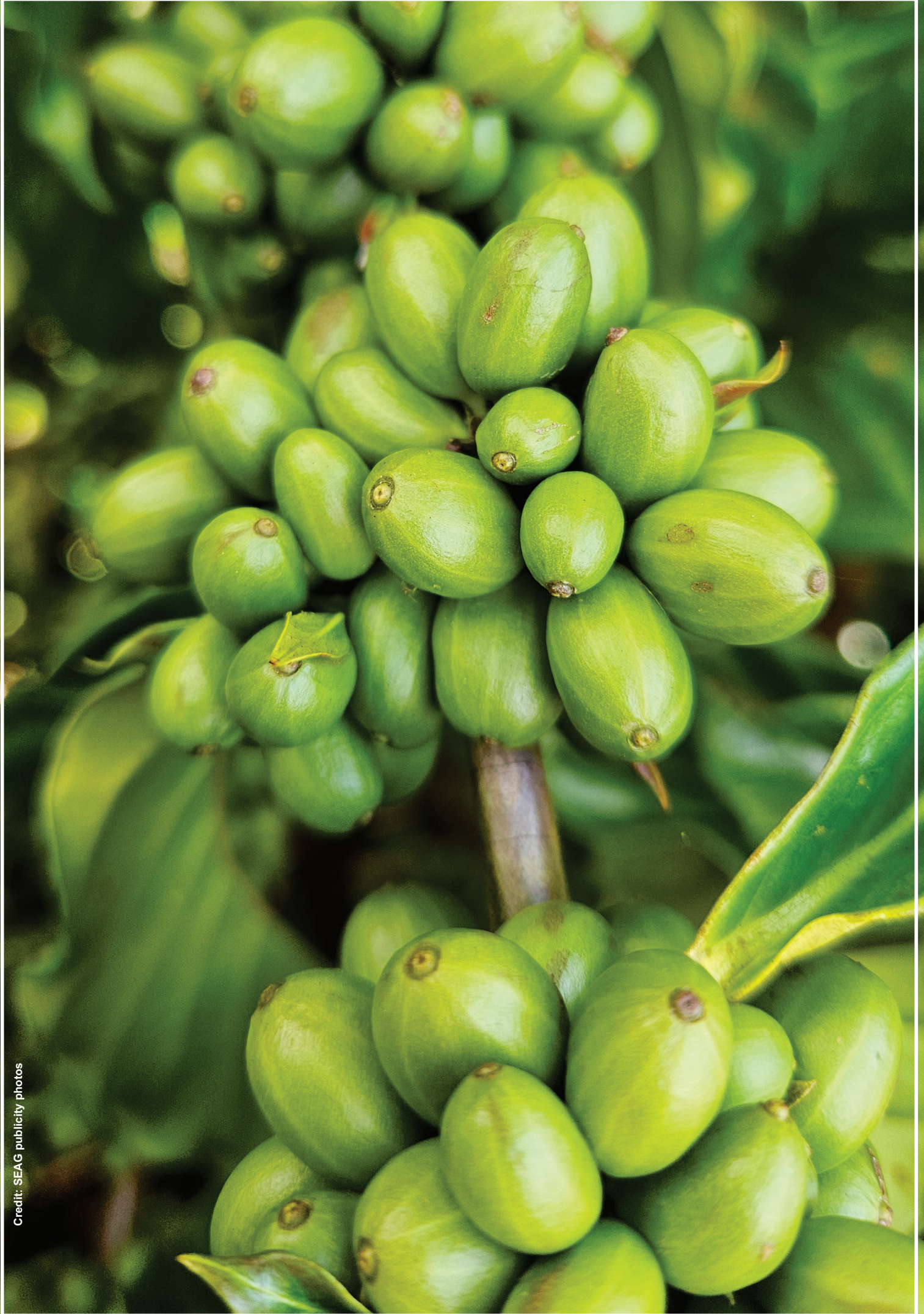
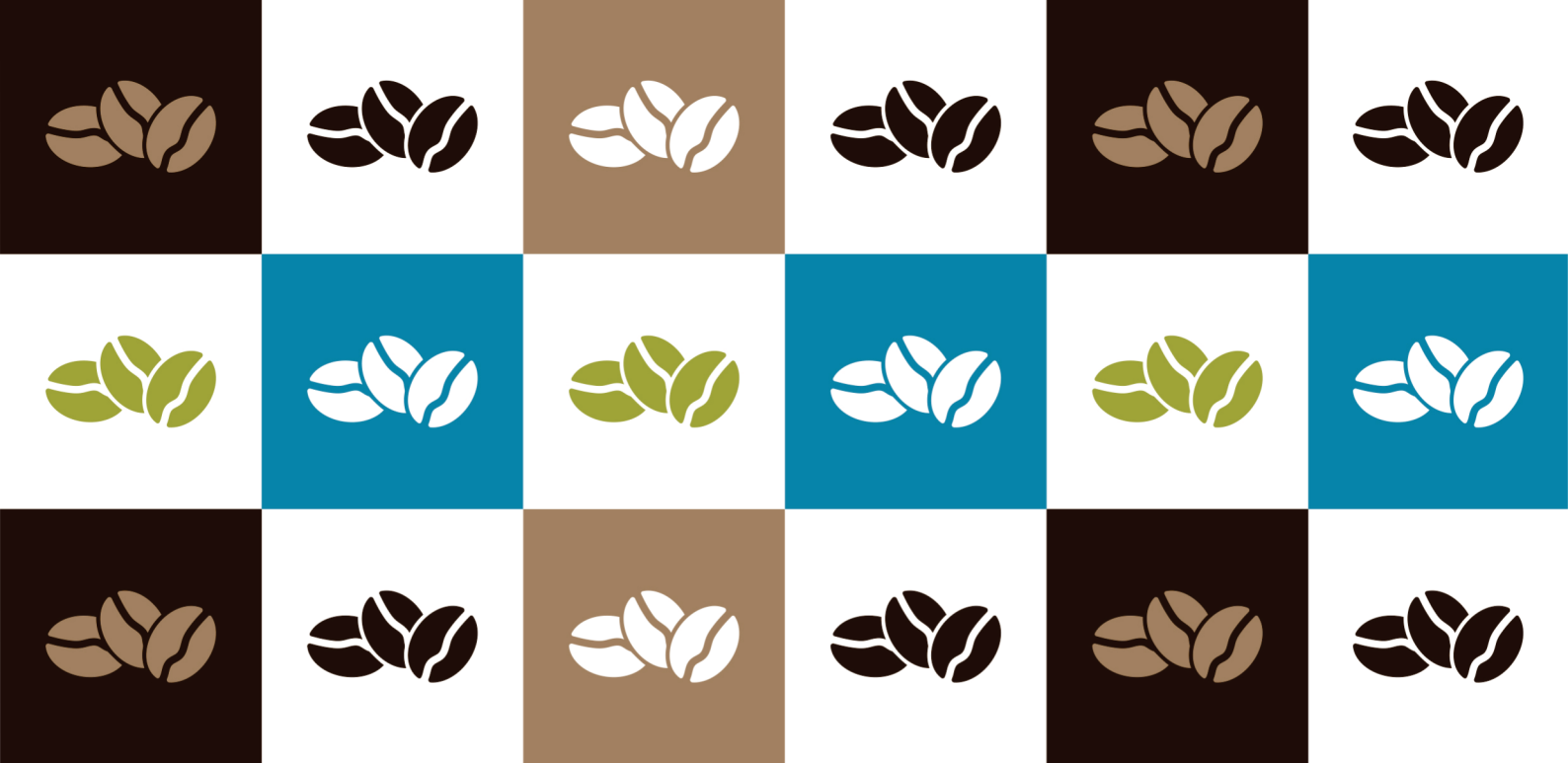


Figure 9A. DP values for "Pair 9", considering the variation in the extraction depth of the soil samples.





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