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Carbon dioxide equivalent balance in coffee plantations

Balanço do dióxido de carbono equivalente em lavouras cafeeiras

Balance de dióxido de carbono equivalente en plantaciones de café

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Abstract
The present study aimed to perform the carbon equivalent balance in coffee plantations grown with two cultivars. It was carried out IN 2021 on a farm in the cities of Guaxupé - MG and Tapiratiba - SP, Brazil. Two plots (A and B) were evaluated, and had been planted in 2018, with a spacing of 3.5 x 0.7 m. Plot A was grown with the cultivar Acaia IAC 474-19, and plot B with the cultivar Catuaí IAC - 99. Emissions were estimated using the GHG Protocol, of the Ministry of Science, Technology, and of the Innovation and Intergovernmental Panel on Climate Change (IPCC). Biomass carbon was quantified after tree felling, determining humidity (%), carbon content (C), and carbon dioxide equivalent estimate (CO_2-eq). Carbon equivalent balance per hectare (CO_2-eq ha^{-1}) was obtained as the difference between sequestered carbon and estimated emissions. Results showed that the equivalent carbon sequestration in coffee biomass within 3.5 years was about 3.6 times greater than emissions. CO_2-eq removal after 3.5 years was 15.15 and 24.92 Mg CO_2-eq ha^{-1} for the cultivars Catuaí IAC-99 and Acaia IAC 474-19, respectively. Emissions throughout the period were 5.05 and 5.77 Mg CO_2-eq ha^{-1} for plots grown with Catuaí IAC-99 and Acaia IAC 474-19. Therefore, the production system evaluated can be considered carbon neutral within 3.5 years.
Keywords: Coffee growing; Greenhouse gases; Carbon sequestration.

Resumo
Objetivou-se no presente estudo realizar o balanço do carbono equivalente em lavouras cafeeiras ocupadas por duas diferentes cultivares. O estudo foi conduzido no ano de 2021, em propriedade agrícola localizada dentro dos municípios de Guaxupé - MG e Tapiratiba - SP, Brasil. Foram avaliadas duas glebas (A e B), plantadas no ano de 2018 com espaçamento 3,5 x 0,7 m. A gleba A ocupada com a cultivar Acaia IAC 474-19 e a gleba B cultivar Catuaí IAC - 99. A estimativa de emissões foi calculada utilizando-se das metodologias *GHG Protocol*, Ministério da Ciência, Tecnologia e Inovação e *Intergovernmental Panel on Climate Change* (*IPCC*). O carbono presente na biomassa foi quantificado a partir do abate das plantas, determinação da umidade (%), teor de carbono (C) e estimativa do dióxido de carbono equivalente (CO_2 eq). O balanço do carbono equivalente por hectare (CO_2 eq ha^{-1}) foi obtido pela diferença entre o carbono sequestrado e as emissões estimadas. Os resultados demonstraram que o sequestro de carbono equivalente na biomassa do cafeeiro em 3,5 anos foi de aproximadamente 3,6 vezes maior que

as emissões. A remoção de CO_2 eq aos 3,5 anos foi estimada em 15,15 e 24,92 Mg CO_2 eq ha^{-1} para a cultivar Catuai IAC-99 e Acaia IAC 474-19 respectivamente. As emissões ao longo do período avaliado foram de 5,05 e 5,77 Mg CO_2 eq ha^{-1} para as glebas cultivadas com Catuaí IAC-99 e Acaia IAC 474-19, portanto o sistema de produção avaliado aos 3,5 anos pode ser considerado carbono neutro.
Palavras-chave: Cafeicultura; Gases de efeito estufa; Sequestro de carbono.

Resumen

Se propuso en el presente estudio realizar el balance de carbono equivalente en plantaciones de café ocupadas por dos cultivares diferentes. El estudio fue realizado en el año de 2021 en una finca ubicada dentro de la municipalidad de Guaxupé - MG y Tapiratiba – SP, Brasil. Fueron evaluadas dos partes de tierra (A e B), plantadas en el año de 2018 con espaciamiento 3,5 x 0,7 m. La parte A ocupada con el cultivar Acaia IAC 474-19 y la parte B con el cultivar Catuaí IAC – 99. La estimación de emisiones se calculó utilizando las metodologias GHC Protocol, Ministério de Ciencia, Tecnología y Innovación y Intergovernmental Panel on Climate Change (IPCC). Se cuantificó el carbono presente en la biomasa a partir del corte de las plantas, determinación de la humedad, % contenido de carbono (C) y estimación del dióxido de carbono equivalente (CO_1 eq). El balance de carbono por hectárea (CO_2 eq ha^{-1}) se obtuvo por la diferencia entre el carbono secuestrado y las emisiones estimadas. Los resultados demostraron que el secuestro de carbono equivalente en la biomasa de las plantaciones de café en 3,5 años fue aproximadamente 3.6 veces mayor que en las emisiones. A los 3,5 años se estimó la eliminación de CO_2 eq en 15,15 y 24,92 Mg CO_2 eq ha^{-1} para el cultivar Catuaí IAC - 99 y Acaia IAC 474-19 respectivamente. A lo largo del período de evaluación, las emisiones fueron de 5,05 y 5,77 Mg CO_2 eq ha^{-1} para las partes de tierra cultivadas con Catuaí IAC - 99 y Acaia IAC 474-19, por lo tanto el sistema de producción evaluado a los 3,5 años puede ser considerado carbono neutro.
Palabras Clave: Cultivo del café; gases del efecto invernadero; secuestro de carbono

1. Introduction

Scenarios of climate changes projected have shown the occurrence of extreme events, increase in global average temperature, imbalance of weather seasons, and compromised availability of natural resources (Abreu; Albuquerque & Freitas, 2015). These consequences may have potential socioeconomic influence on agriculture, economy, and life of the planet's population (Santos; Oliveira & Ferreira Filho, 2022; IPCC, 2014). Therefore, the scientific community has pointed out that these occurrences are related to an increase in Greenhouse Gases (GHG) emissions into the atmosphere, especially linked to the intensification of anthropic activities.

Brazilian agriculture is estimated to contribute with about 75% of CO_2 emissions, 91% of CH_4 emissions, and 94% of N_2O emissions, including forest conversion into farming area (Bayer et al., 2011). However, farming activities may also play a central role in reducing GHG emissions and impacts of climate change, especially due to their ability to remove and fix carbon. In this sense, Vasconcelos et al. (2018) pointed out that agricultural activities and practices can be a sources or sinks of GHGs, as good practices can mitigate gases emissions and contribute to maintenance of environmental services and sustainability of production systems.

Coffee growing stands out as one of the main crops in Brazil and, therefore, has great importance in the national and international scenario (Reichman, 2018; CONAB, 2020). However, during production processes, coffee growing-related activities can also contribute to greenhouse gases emissions (Belizario, 2013; Oliveira Junior et al., 2015). In a case study, Oliveira Junior et al. (2015) noted that GHG emissions in a coffee plantation in southern Minas Gerais State had an annual emission of about 2.13 Mg CO_2-eq ha^{-1}.

In Brazil, academic studies have been carried out seeking to understand sources and representativeness of GHG emissions from coffee growing-related activities. As examples, one can cite those of Belizário (2013), Oliveira Junior et al. (2015), Anderson et al. (2021), and Reis et al. (2021). These studies were based on the projected scenarios of changes in the planet's climate, as well as the growing demand of international markets in search of a low-carbon and more sustainable production chain.

If, on the one hand, coffee trees contribute to GHG emissions, on the other hand, it can effectively remove and hence fixate atmospheric carbon in its vegetative compartments, using its photosynthetic capacity. However, there are few works that determine carbon stock in the vegetative structures of coffee plants. Silva et al. (2013) pointed out that coffee plants, due to their long cycle, can store carbon for many years, which reduces its return time to the atmosphere. Most carbon stock studies in Brazil have been done on forest species, as an example, those by Araújo et al. (2021), Brianezi et al. (2019), Souza et al. (2019), and Gatto et al. (2011).

Quantifying equivalent carbon sequestration by coffee plants and estimating its respective emission per unit area may enable us to perform a CO_2-eq balance. Then, one could verify whether the adopted production system is considered carbon neutral. Carbon equivalent is a metric in which GHG emissions are converted into CO_2-eq through the global warming potential of each gas, as well as conversion of sequestered carbon into CO_2-eq by fitting the molecular mass of CO_2 and C.

Therefore, the present study aimed to perform the equivalent carbon balance in coffee plantations grown with two cultivars.

2. Methodology

2.1 Study Area

The study was carried out in 2021 in the farm São José, which is located within the cities of Guaxupé - MG and Tapiratiba - SP, in Brazil. According to Köppen (1918), the local climate is classified as "*Cwb*" type, which stands out for humid temperate with dry winters and moderately hot summers.

Case study was used as a research method. According to Severino (2007), a case study aims to acquire knowledge about a particular and representative reality, and data must be collected, compiled, and analyzed thoroughly. In this study, carbon balance was determined in two coffee plantations grown with two cultivars of the same age, planted at the farm São José. This is a quantitative research with field data collection in line with studies already performed by Coltri et al. (2011), Silva et al. (2013), and Oliveira Junior et al. (2015). Sampieri, Callada, and Lucio (2013) pointed out that data collection with a quantitative focus uses tools already adopted and validated in previous studies, or may propose new ones supported by the scientific literature, in which case they should be tested and fit.

Firstly, two plots (A and B) grown with the cultivars Acaia IAC 474 - 19 and Catuaí Vermelho IAC - 99 were selected. The plots are in the following geographic coordinates: 21°24'32.28" S latitude, 46°42'54.14" W longitude , and 21°26'5.84"S latitude, 46°44'42.43" W longitude, respectively. Both plots were planted at the beginning of 2018, with a spacing of 3.5 x 0.7 m and a stand of 4,082 plants ha^{-1}. Plot A has an average altitude of 830 m and average plant height of 2.21 ± 0.07 m, whereas plot B has an altitude of 980 m and average plant height of 1.40 ± 0.13.

2.2 Estimation of CO_2-eq sequestration ha^{-1}

For each plot (A and B), six sample plants were randomly selected. These trees were cut down (destructive method) and then separated into distinct vegetative compartments (orthotropic branches, plagiotropic branches, leaves, and roots). Thereafter, total wet mass (kg) of each compartment was weighed on a digital scale. Then, representative samples of about 300 g were taken from each compartment and dried in a forced-circulation air oven at 105 ºC until constant weight, quantifying the percentage (%) of respective moisture content.

Dry samples were ground and sieved through 100-mesh sieve (0.150mm), with percentage (%) of carbon being determined by dry combustion method, using the LECO® brand elemental analyzer. With the result obtained (% C), C-eq sequestration ha^{-1} was estimated for each cultivar (Acaia IAC 474-19 and Catuaí IAC - 99) at 3.5 years of age, considering population density (plants ha^{-1}). Conversion of carbon stock (C) into carbon dioxide equivalent per hectare (CO_2-eq) was performed by the ratio between adjusted molecular mass of CO_2 (44) and carbon (C) mass (12).

Mean annual increment (MAI) for each cultivar was calculated by dividing estimated sequestration in Mg CO_2-eq ha^{-1} by plant age (3.5 years).

2.3 Estimation of CO_2-eq emission ha^{-1}

Estimation of greenhouse gases (GHGs) emissions in Mg CO_2-eq ha^{-1} was carried out based on a survey of consumption of nitrogen fertilizers (kg), correctives (kg), diesel oil (L), gasoline (L), and energy electricity (MWh) used in cultural treatments and activities in planting plots A and B for the 2020/2021 agricultural year.

For nitrogenous fertilizers, emissions were estimated by converting kg of N into N2O, an emission factor of 0.01, and a molecular weight ratio of 44/28, as recommended by the IPCC. It was then converted into CO_2-eq by multiplying N_2O global warming potential (GWP) by 298. Regarding soil correctives, it was calculated using the factor 0.13 to find CO_2-eq emission by multiplying the values obtained by 3.67 (GHG PROTOCOL AGRICULTURA, 2014).

GHG emissions from fossil fuels were calculated from the fractionation of biodiesel (in diesel, anhydrous alcohol, and gasoline) over the agricultural years planting/2019, 2019/2020, and 2020/2021. Then, the amount of diesel, biodiesel, gasoline, and anhydrous alcohol was multiplied by the specific emission factors of CO_2, CH_4, and N_2O (Table 1), and then converted to CO_2-eq, using the global warming potentials (GWPs) 1, 25, and 298, respectively.

Table 1: Reference parameters for calculating greenhouse gas emissions.

Fuel	Calculation factors (Kg GHG $unit^{-1}$)			Source
	CO_2	CH_4	N_2O	
Diesel	2.6810	0.00030	0.000020	GHG Protocol Agricultura (2014)
Biodiesel	2.4990	-	-	GHG Protocol Agricultura (2014)
Gasoline	2.2120	0.00080	0.000026	GHG Protocol (2021)*
Anhydrous alcohol	1.5260	0.00020	0.000010	GHG Protocol (2021)*

* Table of GHG Protocol Conversion (calculation tool). Source: Adapted from GHG Protocol Agricultura (2014) and GHG Protocol (2021).

Indirect CO_2-eq emissions were estimated by multiplying power consumption per hectare (MWh) by the emission factor of the Ministry of Science, Technology, and Innovation (Mg CO_2 MWh^{-1}) for each period (Brasil, 2021).

2.4 Balance of CO_2-eq ha^{-1}

Equivalent carbon balance was calculated by the difference between sequestration in Mg CO_2-eq ha^{-1} for each of the cultivars (Acaia IAC 474-19 and Catuaí IAC 99) and emission estimates (Mg CO_2-eq ha^{-1}) over the period from 2018 to 2021. Results of moisture and carbon content (%) of each vegetative compartment were subjected to analysis of variance (ANOVA), using the F-test. When the F-test was significant, the means were compared using the Tukey's test at 5% significance error. The analyses were performed using the statistical computational software “SISVAR” (Ferreira, 2011).

3. Results and Discussion

3.1 Sequestration of carbon (C) and CO_2-eq

Significant interactions were observed between factors, vegetative compartments, and cultivars for moisture percentage ($F=0.0102$; $p<0.05$). The highest averages were in coffee tree leaves, both for the cultivar Acaia IAC 474-19 (64.53

% ± 2.31) and Catuaí IAC-99 (59.17 % ± 1.67) (Table 2). On the other hand, orthotropic branches had the lowest moisture percentages in both cultivars (Acaia 37.22%; Catuaí 37.69%) (Table 2).

Table 2: Mean moisture values (%) (± standard deviation) in the vegetative compartments of coffee trees of the Catuaí IAC-99 and Acaia IAC 474-19 cultivars.

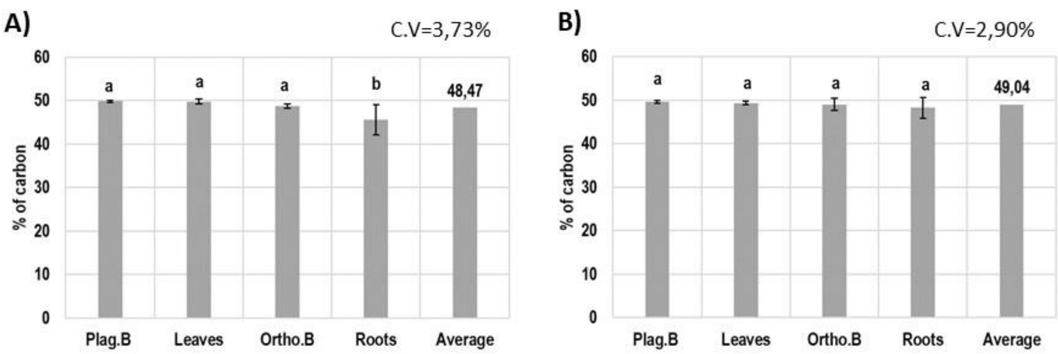
Vegetative Compartment (VC)*	Catuaí IAC 99	Acaia IAC 474-19
	Moisture (%) ± s	
Leaves	59.17 ± 1.67 aB	64.53 ± 2.31 aA
Orthotropic branches	37.69 ± 1.06 bA	37.22 ± 2.94 bA
Plagiotropic branches	48.35 ± 2.16 cB	52.01 ± 4.11 cA
Roots	44.73 ± 4.34 cA	42.62 ± 3.09 dA
Interaction: VC* x Cultivar	0.0102	
C.V. (%) (1)	6.03	

* Vegetative compartment; (1) Coefficient of variation in percentage; means with the same lowercase letter in columns and uppercase in rows do not differ from each other by the Tukey's test at 5% significance level. Source: Authors (2022).

Silva et al. (2013) assessed carbon stock in the soil and in coffee trees and found moisture percentages of 64.81% in leaves and 46.06% in orthotropic branches. Their results reinforce the greater amount of water in coffee leaves than in the other compartments. Coltri et al. (2011) also showed that between 44 and 64% of the wet biomass of *Arabica* coffee trees planted under full sun is composed of water. Therefore, moisture percentage should be determined for vegetative compartment to quantify dry biomass and respective carbon (C) sequestration.

Regarding carbon percentage, no significant interaction was found between vegetative compartments and cultivars (F=0.0980; p>0.05). Laboratory analyses showed that, on average, 48.47% of dry biomass in Catuaí IAC 99 plants (Figure 1A) and 49.04% in Acaia IAC 474-19 plants are made up of carbon (Figure 1B). Similar results were mentioned by Coltri et al. (2011), who found carbon percentages between 49 and 50% in coffee plant dry biomass.

Figure 1: Percentage (%) of carbon in dry biomass of vegetative tissues of coffee plants. Catuaí (A); M.N Acaia (B).



* C.V. = Coefficient of Variation; **Plag.B** = Plagiotropic branches; **Ortho.B** = Orthotropic Branches. Means followed by the same lowercase letters between the bars do not differ from each other by the Tukey's test at 5% significance. Source: Authors (2022).

Total carbon (C) sequestration at 3.5 years was 4.13 and 6.79 Mg C ha^{-1} for the cultivars Catuaí IAC - 99 and Acaia IAC 474-19, respectively. Thus, CO_2-equivalent removal was 15.15 Mg CO_2-eq ha^{-1} for the Catuaí IAC - 99 and 24.92 Mg CO_2-eq ha^{-1} for the cultivar Acaia IAC 474-19 (Table 3). Silva et al. (2013) determined a carbon stock of 33.77 Mg CO_2-eq ha^{-1} for the cultivar Catuaí. Such a difference from may be related to plant development stage.

Table 3: Sequestration of carbon (C) and carbon dioxide equivalent (CO_2-eq) in plantations of Catuaí IAC-99 and Acaia IAC 474-19 coffee of 3.5 years (Mg CO_2-eq ha^{-1}) and mean annual increment - MAI (Mg CO_2-eq ha^{-1} $year^{-1}$).

Vegetative Compartment	Carbon		Carbon Dioxide Equivalent		MAI (1)	
	Catuaí (2)	Acaia (3)	Catuaí (2)	Acaia (3)	Catuaí (2)	Acaia (3)
	Mg C ha^{-1}		Mg CO_2-eq ha^{-1}		Mg CO_2-eq ha^{1} $year^{-1}$	
Leaves	1.13	0.92	4.15	3.38	1.18	0.96
Orthotropic B.*	1.09	2.93	4.00	10.75	1.14	3.07
Plagiotropic B.**	1.19	1.80	4.36	6.61	1.24	1.88
Roots	0.72	1.14	2.64	4.18	0.75	1.19
Total	4.13	6.79	15.15	24.92	4.31	7.10

*Orthotropic branches; **Plagiotropic branches; (1) Mean annual increment; (2) Catuaí Vermelho IAC - 99; (3) Acaia IAC 474-19. Source: Authors (2022).

Our results showed that Acaia IAC 474-19 trees sequestered more carbon per unit area (ha) than Catuaí IAC-99 trees of the same age. This finding can be explained by individual traits and size of each cultivar. At the time of the study, Acaia IAC 474-19 plants had an average height of 2.21 m ± 0.07, while Catuaí had 1.40 m ± 0.13. The highest amount of CO_2-eq stored was estimated in orthotropic branches of Acaia IAC 474-19 plants (10.75 Mg CO_2-eq ha^{-1}), an increment of 6.75 Mg CO_2-eq ha^{-1} above that of Catuaí IAC – 99 trees. Still, one must reiterate that orthotropic branches had lower % moisture in both cultivars (37.22 and 37.69 %, respectively; Table 2). Thus, our findings suggest that cultivars of greater sizes and trunk diameters can sequester and store a greater amount of dry matter and, consequently, carbon equivalent.

Carbon equivalent MAI was 4.31 Mg CO_2-eq ha^{-1} $year^{-1}$ for Catuaí IAC 99 and 7.10 Mg CO_2-eq ha^{-1} $year^{-1}$ for Acaia IAC 474-19. In Eucalyptus monocrops with different spatial arrangements at 32 months of age, Brianezi et al. (2019) reported a MAI of 25.39 ± 6.68 Mg CO_2-eq ha^{-1} $year^{-1}$. Thus, the MAIs sequestered by the cultivars Catuaí and Acaia were 16.97 and 27.96% of that by Eucalyptus plants.

3.2 Estimate of CO_2-eq emissions ha^{-1}

Total GHG emissions from the planting year 2018 to 2021 was 5.04 and 5.77 Mg CO_2-eq ha^{-1} for the cultivars Catuaí IAC-99 and Acaia IAC 474-19, respectively (Table 4). Annual average was 1.44 Mg CO_2-eq ha^{-1} in the area grown with Catuaí and 1.65 Mg CO_2-eq ha^{-1} in that with Acaia plants. Therefore, when considering that similar management practices were adopted in both plots, no expressive differences were evidenced between total emissions and annual averages. Remarkably, nitrogen fertilizers were the main sources of emissions, followed by fuel consumption, in both plots evaluated (Table 4).

Oliveira Junior et al. (2015) surveyed GHG emissions using the carbon equivalent method in a coffee plantation and determined an estimate of 2.13 Mg CO_2-eq ha^{-1}, with nitrogen fertilizers also appearing as the main annual emission source with about 1.01 Mg CO_2-eq ha^{-1}, representing 47.5% of total emissions.

Table 4: Estimate of CO_2-equivalent emissions (Mg ha^{-1}) from Catuaí IAC 99 and Acaia IAC 474-19 plots. Agricultural years: from planting to 2020/2021 - 3.5 years.

Source	GHG emission*			Annual Average	Total	*Fr* [(1)]
	Planting year/ 2019[(2)]	2019/2020	2020/2021	-	-	-
		Mg CO_2-eq ha^{-1}		Mg CO_2-eq ha^{-1}		(%)
Catuaí IAC-99	-	-	-	-	-	-
Nitrogen fertilizers	0.24	1.71	1.56	1.00	3.51	69.64
Soil correctives	-	0.63	-	0.18	0.63	12.50
Fossil fuels	0.26	0.39	0.20	0.24	0.85	16.86
Electric power	-	0.02	0.03	0.01	0.05	0.99
Total	0.50	2.75	1.79	1.44	5.04	-
Acaia IAC 474-19	-	-	-	-	-	-
Nitrogen fertilizers	0.59	2.48	1.33	1.25	4.39	76.08
Soil correctives	0.26	-	-	0.07	0.26	4.50
Fossil fuels	0.29	0.45	0.32	0.30	1.06	18.37
Electric power	0.01	0.02	0.02	0.01	0.05	0.86
Total	1.15	2.95	1.67	1.65	5.77	-

* Greenhouse gases in carbon dioxide equivalent - CO_2-eq. [(1)]percent relative frequency [(2)] from planting in the early 2018 to 2019. Source: Authors (2022).

3.3 Balance of CO_2-eq ha^{-1}

Carbon balance showed that coffee plantations at 3.5 years old sequestered more CO_2-eq ha^{-1} than emitted (Table 5). Sequestration of CO_2-eq ha^{-1} in coffee plant biomass was 3.0 and 4.3 times greater than emissions in the study plots (Table 5). Emission-sequestration balance in the area grown with Catuaí was 10.11 Mg CO_2-eq ha^{-1} and in the area with Acaia 19.15 Mg CO_2-eq ha^{-1}. Thus, mean annual increments (MAIs) were 2.88 and 5.47 Mg CO_2-eq ha^{-1} $year^{-1}$ in the areas grown with Catuaí IAC-99 and Acaia IAC 474-19, respectively (Table 5).

Table 5: Balance of CO_2-equivalent (Mg ha^{-1}) in plots grown with the cultivars Catuaí IAC-99 and Acaia IAC-474-19 at 3.5 years.

Cultivar	Sequester	Estimate (GHG)	Balance
	Mg CO_2-eq ha^{-1}	Mg CO_2-eq ha^{-1}	Mg CO_2-eq ha^{-1}
Balance – 3.5 years	-	-	-
Catuaí IAC-99	15.15*	5.04	10.11
Acaia IAC-474-19	24.92*	5.77	19.15
Balance – annual	-	-	-
Catuaí IAC-99	4.32 [(1)]	1.44[(1)]	2.88[(1)]
Acaia IAC-474-19	7.12 [(1)]	1.65[(1)]	5.47[(1)]

* Values at 3.5 years of age; [(1)] Annual average. Source: Authors (2022).

Therefore, our findings indicate that coffee production system at 3.5 years of age can be considered carbon neutral. When dividing the CO_2-eq sequestration balance of the biomass at 3.5 years (Table 5) by the average annual emission (1.44 and 1.65 Mg CO_2-eq ha^{-1}), the values found are enough to ensure such neutrality for a time horizon of another 7 and 11 years, without considering other carbon increments that will occur during plant development, including that immobilized in the soil.

In this way, coffee plantations can effectively contribute to greenhouse gases removal from the atmosphere.

4. Conclusion

Under the conditions of this study, we can conclude that equivalent carbon sequestration in the plantations evaluated at 3.5 years of age was around 3.6 times greater than emissions.

The cultivar Acaia IAC 474-19 sequestered more CO_2-eq ha^{-1} than did Catuaí Vermelho IAC - 99 plants of the same age, with greater representation for orthotropic branches.

The production system evaluated at 3.5 years can be considered "zero carbon" since it removed more CO_2-eq than it emitted.

Therefore, new studies of the equivalent carbon balance in coffee trees of different ages, cultivars, and production arrangements must be developed to characterize and demonstrate "CO_2-eq footprint" under different scenarios.

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