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Brazilian Coffee in the Carbon Market: A Prospective Analysis of Financial Viability and Effectiveness

Cafés do Brasil no Mercado de Carbono: uma Análise Prospectiva de Viabilidade e Efetividade.

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Abstract: This article prospectively analyzes the financial viability of integrating coffee cultivation into Brazil's regulated carbon market. The analysis, based on the potential reduction of greenhouse gas (GHG) emissions and the profitability of carbon credit trading, employed microeconomic analysis to estimate the minimum viable scale of the plantation. Using the projected minimum area, the study inferred the potential participation of Brazilian coffee cultivation from census data. The results indicated low effectiveness of the cap-and-trade policy for the sector, as fewer than 12% of coffee farms reach the minimum viable area to trade credits. The study concludes that mechanisms to reduce certification costs are necessary to enhance policy effectiveness, promote environmental conservation, and foster social inclusion.

Keywords: Carbon market, Coffee farming, financial viability, effectiveness, cost-benefit.
JEL Classification: Q52; Q54; Q58; Q14

Resumo: Este artigo analisa prospectivamente a viabilidade financeira da inserção da cafeicultura no mercado de carbono regulado no Brasil. A análise, baseada no potencial de redução de emissões de gases de efeito estufa (GEE) e na rentabilidade do comércio de créditos, utilizou microeconomia para estimar a escala mínima viável da lavoura. Com as projeções de área mínima, inferiu-se o potencial de inserção da cafeicultura brasileira a partir de dados censitários. Os resultados indicaram baixa efetividade da política de cap and trade para o setor, pois menos de 12% das propriedades cafeeiras atingem a área mínima viável para comercializar os créditos. Conclui-se pela necessidade de adoção de mecanismos que reduzam os custos de certificação, buscando maior efetividade da política, com conservação ambiental e inclusão social.
Palavras-chave: Mercado de carbono, Cafeicultura, viabilidade financeira, efetividade, custo e benefício.
Classificação JEL: Q52; Q54; Q58; Q14

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1. Introduction

Certain contemporary developments are shrouded in controversy and disagreement. The opinions expressed by both experts and laypeople on some topics have become so divergent that it often feels as though entirely different subjects are being discussed. The constructive aspect of any controversy—the pursuit of rigorous explanation—tends to vanish, giving way to a sense of intellectual helplessness and an inability to develop an informed opinion on the matter. One of the most controversial contemporary events is undoubtedly “climate change”, perhaps the most emblematic issue of the current moment.

Members of the scientific community warn of imminent negative consequences resulting from a rise in the planet’s average temperature. In contrast, prominent politicians challenge such claims, arguing that they generate unnecessary alarm and lead to substantial financial costs based on what they consider weak evidence of a poorly understood phenomenon. Amid such controversy, ordinary citizens, unfamiliar with the technical aspects of the issue, are left bewildered as they witness heavy rains during traditionally dry seasons, increasingly frequent natural disasters, and prolonged heatwaves and droughts that appear unlike anything previously observed in their lifetimes.

Driven by the precautionary principle—which holds that preventive action tends to generate greater net benefits than inaction under conditions of uncertainty—nations have been negotiating alternatives to mitigate the (potential, for some, and real, for others) negative consequences of rising global average temperatures. Particularly in Brazil, **the country has committed to reducing its greenhouse gas (GHG) emissions by 48% by 2025 and 53% by 2030**, relative to 2005 levels. In addition, in 2023, Brazil reaffirmed its pledge to **reach net-zero emissions by 2050**. This goal implies that all emissions must be offset by carbon capture sources, such as reforestation, ecosystem restoration, or other technologies (BNDES, 2024)[3]. In this context, Decree No. 11,550/2023 was enacted in June 2023 to establish guidelines for the development of sectoral plans for climate change mitigation (BRASIL, 2023).

To meet their GHG (greenhouse gas) emissions reduction targets, several countries have implemented tradable permit systems for these pollutants, known as regulated carbon markets. The largest carbon market is the European Union Emissions Trading System (EU ETS), which sets strict emission limits for industries and requires companies to purchase allowances to emit carbon. Other major regulated markets include California’s Cap-and-Trade Program and China’s Emissions Trading Scheme (ETS), the most recent of these initiatives, which already stands out due to its large trading volume. In addition to regulated markets, there are voluntary carbon market initiatives, in which companies and individuals purchase carbon credits to offset their emissions without being legally required to do so.

Carbon credit prices vary significantly between regulated and voluntary markets and fluctuate over time. In regulated markets, prices are influenced by the limited supply of

[3] See NDC Dashboard – Our Contribution to Brazil’s Emissions Reduction Targets (bndes.gov.br)

credits and the pressure to reduce emissions. Price volatility can be explained by factors such as changes in environmental policies, economic fluctuations, variations in demand for carbon offsets, and regulatory uncertainty.

Agriculture holds significant potential to contribute to these markets, particularly through soil carbon sequestration and agroforestry practices. Low-cost methods such as no-till farming, the use of organic fertilizers, sustainable pasture management, and agroforestry systems can either reduce GHG emissions or sequester carbon. These benefits can be converted into carbon credits, creating a new source of income for farmers. However, the integration of agriculture into these markets still faces challenges, such as the need for robust methodologies for measuring, reporting, and verifying emission reductions, as well as the development of policies to encourage participation.

This study is situated within this context. It offers a prospective analysis of the potential integration of coffee cultivation into Brazil's regulated carbon market, based on its capacity to reduce GHG emissions and the potential profitability of credit trading. The analysis begins by assessing the financial viability of carbon credit trading as a secondary activity within coffee production, aiming to estimate the minimum viable farm size—in terms of cultivated area—required to participate in the market. This estimated threshold is then compared with agricultural census data on coffee-producing establishments to evaluate the sector's potential for integration into the carbon market. The findings highlight the potential effectiveness of the regulated carbon market as a public policy tool for the coffee sector and provide evidence to inform the design of implementation strategies, including the development of Sectoral Plans for Climate Change Mitigation.

To develop its argument and present the results, the article is organized into four main sections, in addition to this Introduction and the Conclusion. The next section provides a brief overview of the interplay between international and national climate change initiatives, with a focus on federal policies primarily aimed at mitigation. This discussion is followed by an examination of how agricultural activities—particularly coffee cultivation—fit within this mitigation framework for GHG emissions. Section 3 outlines the core conceptual foundations of what is commonly referred to as the carbon market. Section 4 presents the materials and methods employed in the analysis. Section 5 introduces cost and benefit estimates related to the participation of coffee cultivation in Brazil's regulated carbon market, and summarizes the results of the prospective assessment of the sector's financial viability for engaging in such a market.

2. GHG Emissions: Mitigation Plans, Agriculture, and Coffee Cultivation In Brazil

In fulfillment of its commitments under the United Nations Framework Convention on Climate Change (UNFCCC), Brazil enacted Law No. 12,187 on December 29, 2009, establishing the National Policy on Climate Change (PNMC – *Política Nacional sobre Mudança do Clima*). To facilitate the achievement of its emission reduction targets, the law requires the formulation of sector-specific mitigation and adaptation plans across local, regional, and national levels.

The Sectoral Mitigation Plans cover several areas listed in the PNMC, including the agricultural sector. In this context, it is important to note that, according to Freitas et al. (2016), GHG emissions from agriculture and livestock reached 423.1 million tons of CO_{2eq} in 2014, accounting for 27.2% of Brazil's total emissions. One significant measure to reduce the agricultural sector's impact is Decree No. 10,606, dated January 22, 2021, which instituted the Integrated Information System for the Sectoral Plan for Consolidation of a Low-Carbon Economy in Agriculture (SIN-ABC – *Sistema Integrado de Informações do Plano Setorial para Consolidação de uma Economia de Baixa Emissão de Carbono na Agricultura*), which is coordinated by the Brazilian Agricultural Research Corporation (Embrapa – *Empresa Brasileira de Pesquisa Agropecuária*), among other agencies and institutions (BRASIL, 2021).

Specifically regarding the coffee sector, the Deliberative Council of the Coffee Policy (CDPC – *Conselho Deliberativo da Política do Café*)[4] identified the theme "Environmental services related to climate change and coffee production systems" as a priority for the Coffee Research and Development Program (PNP&D/Café – *Programa de Pesquisa e Desenvolvimento do Café*), underscoring the importance of integrating coffee cultivation into climate change mitigation policies (Embrapa, 2020).

It is relevant to highlight that Brazil is the world's largest coffee producer and exporter, as well as the second-largest consumer of the beverage. According to Guerra et al. (2021), Brazil's coffee harvest in 2020 reached 63.1 million 60kg bags, cultivated over 2.162 million hectares, with an average productivity of 33.48 bags per hectare. The Gross Production Value amounted to R$ 36 billion that year. Brazilian coffee production is generated by more than 264,000 producing establishments across 1,448 municipalities, with 78% of these farms classified as family agriculture (IBGE, 2019).

In late 2023, the Chamber of Deputies approved Bill No. 2148/15, which creates the Brazilian Emissions Trading System (SBCE – *Sistema Brasileiro de Comércio de Emissões de Gases de Efeito Estufa*), establishes emission caps, and creates a market for trading emission allowances. After amending the text previously approved by the Federal Senate, the bill has returned to the upper house for further review. Additionally, Decree No. 11,550/2023 regulates the Interministerial Committee on Climate Change (CIM – *Comitê Interministerial sobre Mudança do Clima*), which is empowered, among other duties, to coordinate and define federal action guidelines related to the instruments established by the PNMC.

[4] The CDPC, which is part of the organizational structure of the Ministry of Agriculture, Livestock and Food Supply (MAPA – *Ministério da Agricultura, Pecuária e Abastecimento*), is responsible, among other duties, for "approving the National Coffee Research and Development Program, as proposed by the Coordination of the Brazilian Coffee Research and Development Consortium," as established in Article 2, Item VI, of Decree No. 10,071 of October 17, 2019 (BRASIL, 2019).

One of the instruments of the PNMC is the Brazilian Emissions Reduction Market, which establishes the trading of securities representing certified avoided greenhouse gas emissions (BRASIL, 2009). Thus, it can be inferred that the Brazilian Emissions Reduction Market envisions or anticipates the establishment of a tradable permit system (cap-and-trade). The regulation of the carbon market in Brazil represents a step toward creating incentives aimed at curbing GHG emissions and reducing the climate impact of productive activities. Emerging from the near-monopoly of command-and-control instruments in Brazilian environmental governance, this financial and economic alternative introduces carbon pricing. Ideally, this measure reflects recognition of the importance of establishing specific mechanisms to address climate change and promote the transition to a more sustainable economy.

In the specific case of coffee production, the existence of a carbon market where sellers and buyers of avoided or sequestered carbon credits interact enhances the pursuit of economic efficiency in land-use decisions. Moreover, the trading of carbon credits by coffee producers can increase the effectiveness of GHG reduction policies and encourage the adoption of best agricultural practices in coffee plantations, thereby contributing to the sustainability of Brazilian coffee cultivation—both in terms of environmental conservation and the generation of rural income and employment.

3. Carbon Credit Market: Conceptual Aspects

Carbon pricing can theoretically occur in two ways: either through the regulator setting a price that reflects the economic (social) value of carbon, or via the establishment of a carbon market where a carbon price emerges from the negotiation between buyers and sellers of carbon credits (or carbon allowances). The latter approach is commonly referred to in the environmental economics literature as a tradable permit system, or cap-and-trade, in the terminology favored by U.S. environmental policy makers.

Tradable permits were originally conceived as a pollution control mechanism in the early 1970s (Godoy and Saes, 2015). This policy instrument aims to internalize the cost of environmental degradation by creating a market for the use of ecosystem services, such as absorption and dilution. In doing so, it complements the market of each polluting industry by assigning a cost to natural inputs that were previously treated as free goods. Under a tradable permit system, the regulator sets an upper limit on allowable pollution or environmental degradation within a given geographic area. This cap is then allocated among polluting agents in the form of permits, which may be distributed for free, sold, or allocated through a combination of both mechanisms.

Each agent is allowed to pollute or degrade the environment only up to the total amount covered by the permits it holds—either received or purchased. If an agent emits or degrades less than the amount permitted, the surplus—often referred to as pollution allowances or credits—can be traded with other eligible agents operating within the same regulatory area. Through this approach to controlling aggregate levels of environmental degradation or pollution, it becomes possible to establish a total number of permits or quotas equivalent to the assimilative, carrying, and/or sustainable capacity of the environment within a defined geographic area.

According to Sterner and Coria (2012), this environmental policy instrument establishes property rights related to the entitlement to pollute or degrade the environment and helps to eliminate or reduce negative externalities inherent in the absence of property rights or the public good nature of the environment. Thus, the creation of a market with a pricing mechanism to trade the right to generate negative externalities incentivizes the reduction of adverse effects from decisions regarding the use of environmental assets.

Another relevant conceptual aspect, noted by Baranzini et al. (2017), is that emitters face heterogeneous marginal costs of reduction. Under perfect information, each emitter selects an emission reduction level where the marginal abatement cost equals the permit price. This mechanism allows tradable permits to flexibly allocate reduction efforts efficiently by enabling cost compensation across emitters with varying abatement expenses, thereby reinforcing the equimarginal principle and promoting overall economic efficiency.

Tradable permits allow market agents—producers or landowners—to capture gains from decisions that reduce their environmental impacts. This potential gain serves as a significant motivation. It is important to highlight that, according to Schmalensee and Stavins (2017), the high effectiveness of this instrument is related to clearly defined property rights and a competitive market that enables traders to realize these gains. Consequently, excessive restrictions on the use of offsets can lead to a constrained market that is ineffective for cost containment. Additionally, property rights must convey a sense of permanence to influence costly investments and business decisions. Furthermore, tradable permits do not eliminate the need for significant penalties for non-compliance (Schmalensee and Stavins, 2017).

Despite the attractiveness of the instrument, tradable permits must undergo the usual criteria for evaluating environmental public policies. In this regard, Perman et al. (2003) emphasize cost-effectiveness evaluation, whereby an instrument is considered cost-effective if it achieves its target at a lower total cost than any alternative. Cost-effectiveness is clearly a desirable attribute of an instrument. Using a cost-effective instrument involves allocating the minimum amount of resources necessary to achieve a given target level of environmental degradation or pollution at the lowest total economic cost. Therefore, the use of cost-effective instruments is a necessary condition for achieving an optimal allocation of resources (Perman et al., 2003).

Perman et al. (2003) further caution that when transaction costs are included in comparisons of relative costs, the cost-effectiveness rankings of policy instruments may change. Moreover, as originally explored by Coase (1937), the magnitude of transaction costs can enable or hinder the functioning of a market. Such a dynamic could potentially compromise the effectiveness of an environmental policy based on tradable permits.

Accordingly, this study—a prospective analysis of the viability and effectiveness of carbon trading derived from coffee cultivation—also evaluates transaction costs, particularly those related to carbon credit certification, which have proven to be relatively significant. A comparative study of transaction costs in carbon offset projects conducted by Cacho *et al*. (2013) indicated the infeasibility of smaller-scale ventures in terms of productive area. Consequently, these authors highlight the need to reduce transaction costs to enable smaller-scale projects and propose three strategies to achieve this: implementing collective projects to share costs; leveraging existing infrastructure and management capacity; and lowering information costs, especially through streamlined methodologies for implementation and monitoring (Cacho *et al*., 2013).

4. Materials and Methods

Financial viability is assessed within the conceptual framework of microeconomic equilibrium pricing and profit maximization for carbon credit trading as a complementary activity to coffee production. Based on this assessment, the potential scale, in terms of cultivated area, of coffee farms able to trade carbon credits is estimated. The firm is taken as the unit of analysis, represented by the individual coffee producer. While the primary activity is the production of raw coffee beans, carbon credit trading in a regulated market is considered a potential secondary activity.

It is important to underscore that carbon credits in regulated markets are standardized products, treated as equivalent across producers and countries by market participants worldwide. These characteristics classify carbon credits as commodities, according to the definition by Krugman and Wells (2016). Additionally, using the same authors' definition, the regulated carbon market can be considered a perfectly competitive market, in which all producers and consumers are price takers.

Thus, the estimation of the equilibrium price and profit maximization for carbon trading, as a secondary activity to coffee cultivation, assumes that an individual producer cannot influence the market price. Therefore, the profit maximization and equilibrium price problems consider the producer as a price taker, according to Nicholson and Snyder (2012) and Krugman and Wells (2016). After estimating the equilibrium price and profit-maximizing output levels, it is possible to determine the minimum viable scale for carbon trading and the optimal production level. Using these two indicators, the quantity of carbon credits to be supplied by coffee producers can be assessed.

4.1. Equilibrium Price: From What Production Level Is the Activity Profitable?

The equilibrium price indicates the minimum production level at which a given activity becomes profitable. This information allows inferring the minimum production scale that is financially viable. Thus, production levels are profitable when the market price exceeds the minimum average total cost of the activity. Krugman and Wells (2016), for instance, develop this analysis for agricultural commodities using the following mathematical representation.

$$Profit = TR - TC \quad (1)$$

$$\frac{Profit}{Q} = \frac{TR}{Q} - \frac{TC}{Q} \quad (2)$$

Where:
TR = Total Revenue; TC = Total Cost; and Q = Quantity

Since TR/Q is the average revenue, which equals the price in a perfectly competitive market, and TC/Q is the average total cost, profit can be set to zero to find the minimum non-negative profit point, where Average Total Cost equals Price.

$$0 = P - ATC \quad (3)$$

$$P = ATC \quad (4)$$

Based on Krugman and Wells (2016), the rule to determine whether a producer earns a profit depends on comparing the market price of the good with the producer's minimum average total cost. Thus, if the market price exceeds the minimum average total cost, the producer earns a profit; if it is below, the producer incurs a loss. Finally, if the market price equals the minimum average total cost, the producer breaks even.

4.2. Profit Maximization: What Production Level Results in Maximum Profit?

Profit-maximizing agents make decisions "at the margin." The producer adjusts controllable variables until no further profit increase is possible. This profit maximization problem is represented by Nicholson and Snyder (2012) as:

$$Max\ [P * Q - TC(q)] \quad (5)$$

The first-order condition for profit maximization is:

$$P - MC(q) = 0 \quad (6)$$

Where $MC(q)$ is the marginal cost of producing an additional unit of output. Thus:

$$MC(q) = P \quad (7)$$

Therefore, profit maximization occurs at the production level where marginal cost equals the market price, given the previously mentioned characteristics of perfect competition. This production level coincides with the break-even point, at which the producer covers fixed costs as well, since variable costs are covered by the difference between the selling price and the variable cost per unit. This difference is also known as the contribution margin.

This approach relies on the distinction between fixed costs, which do not vary with production volume, and variable costs, which increase or decrease according to output. It helps determine the number of product units that must be sold for the producer to break even, without incurring losses or gains.

Based on this conceptual framework, empirical evidence is sought for the specific case of coffee cultivation. As is well known, this activity is characterized by a predominance of fixed costs, leading to increasing returns to scale[5] up to the point where the coffee farm reaches its maximum cultivated area. Beyond that point, the cost of expanding the area significantly raises the marginal cost. This cost may therefore exceed the estimated market prices for carbon credits. Thus, once the minimum viable production level for carbon credits and the profit-maximizing output level are obtained, it becomes possible to estimate the quantity of credits that can be supplied by coffee growers. Naturally, there is also the possibility that the market price level is below the equilibrium price. In this case—as previously noted—no carbon credit supply would be observed.

Based on potential outcomes under different carbon credit price scenarios and the associated costs for coffee growers to adopt production alternatives that generate such credits, it is possible to assess the potential integration of Brazilian coffee farming into the carbon market. The simulations presented in this study rely on census data from coffee-producing rural establishments, as will be detailed in the following sections.

4.3. Benefit projections

Regarding the benefits—specifically the amount of carbon credits generated per hectare—this analysis draws on a study that compared the carbon balance (emissions minus sequestration) in coffee farms using conventional management practices with that of farms adopting best practices aimed at increasing carbon stocks. In this context, Arellano and Hernández (2023) recommend the proper use of fertilizers, regular monitoring of soil fertility, the incorporation of functional trees (such as shade or nitrogen-fixing species) into coffee plantations, soil conservation practices, and the use of biofertilizers, among other actions, to reduce carbon emissions. When comparing different coffee production systems

[5] Increasing returns to scale, also known as economies of scale, occur when the long-run average total cost decreases as output increases (Krugman and Wells, 2016).

in Central America, Arellano and Hernández (2023) found that the amount of carbon stored in aboveground biomass ranged from 53.6 Mg/ha in traditional polycultures to 9.7 Mg/ha in full-sun monocultures.

Research conducted at the Federal University of Lavras in a Brazilian coffee farm linked varying NPK fertilizer application rates to productivity levels and greenhouse gas (GHG) emissions. The results indicated that the economically optimal fertilizer application reduced emissions by 18.86%, equivalent to 1.40 tCO_2 eq ha^{-1} (Oliveira, 2015). In a study focused on full-sun monoculture coffee plantations in three regions of the state of Minas Gerais[6], the Cecafé and Imaflora (2022) report indicated that good agricultural practices were effective in increasing carbon stocks by an average of 7.58 tCO_2eq ha^{-1} per year, compared to conventional management practices[7]. Given the representativeness of the farms in that study in relation to Brazilian coffee production, the annual average carbon stock increase of 7.58 tCO_2eq $^{ha-1}$ reported by Cecafé and Imaflora (2022) was used as a reference for calculating total revenue.

To estimate the revenue of coffee farms concerning the price received per carbon credit, possible carbon credit prices were estimated. First, a price coefficient over time was calculated based on 2,583 daily price observations spanning 10 years, from September 13, 2012, to September 12, 2022, of the closing prices of the Intercontinental Exchange (ICE) Global Carbon Futures Index[8], commonly known as Carbon Emissions Futures.

Subsequently, 30 stochastic simulations were performed for each day, using Monte Carlo methods as described by Kroese et al. (2011), where a random component caused prices to vary proportionally to the daily standard deviation, as represented below:

$$PSim = PEst_t + (-2 * SDD\mathrm{ay} + 4 * SDDay_t * Random) \quad (8)$$

Where:

$PSim$ = Simulated price;
$PEst$ = Estimated price;
$SDDay$ = Deviation of the estimated price relative to the observed daily price;
$Random$ = Random component varying between 0 and 1;
t = Quotation day index, ranging from 1 to 2,583; and

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[6] The sample included 40 farms located in three regions of the state of Minas Gerais, Brazil: Cerrado, Matas de Minas and Sul de Minas. Minas Gerais accounts for approximately half of Brazil's coffee production.
[7] The good practices considered in the study include techniques such as intercropping, preference for organic and organomineral fertilizers, integrated pest and disease management, fertigation in areas prone to water deficit, and returning coffee husks (a byproduct of coffee processing) to the soil.
[8] This index is composed of prices from the world's four most traded carbon markets: the European Union Emissions Trading Scheme (EU ETS), the Western Climate Initiative (California Cap-and-Trade Program), the Regional Greenhouse Gas Initiative (RGGI), and the UK Emissions Trading Scheme (UK ETS). Historical daily price data are available at: https://www.ice.com/products/82118761/Global-Carbon-Index-Futures.

i = Simulation index, ranging from 1 to 30.

Finally, the mean of the simulations for the most recent day was taken as the median projected price (Price 2), accompanied by a higher price (Price 3) and a lower price (Price 1), calculated based on the standard deviation of the 30 simulations for the most recent period, as follows:

$$Price1 = Price2 - \frac{2*SDSim}{\sqrt{30}} \tag{9}$$

$$Price3 = Price2 + \frac{2*SDSim}{\sqrt{30}} \tag{10}$$

Where $SDSim$ is the standard deviation of the 30 simulations for the most recent t period.

Thus, the highest and lowest prices tend to be further apart as a function of the standard deviation of the prices observed between September 13, 2012, and September 12, 2022. This method makes it possible to establish a margin between price projections and, consequently, projected benefits.

4.4. Cost Projections

The regulated carbon market is still under development in Brazil. There is a high degree of uncertainty regarding the costs and benefits associated with the trading of carbon credits—particularly for coffee producers—under the assumption that the market will, in fact, allow for such participation. Nevertheless, this possibility must be taken into account so that the design of the cap-and-trade policy incorporates relevant information from different sectors, especially the coffee sector.

The main sources of GHG emissions in coffee production stem from the use of fertilizers, land-use change, farm management practices—including the use of agricultural machinery—and post-harvest processing. These emissions can be significantly reduced through the adoption of good practices and technological solutions that either replace emission-generating processes (carbon sources) or offset emissions through carbon absorption (carbon sinks).

The study by Nab and Maslin (2020) contributed to the quantification of GHG emissions in coffee farming by comparing a conventional production system with a sustainable one, using the carbon footprint methodology. The results for the farming stage, reproduced in Table A.3 of Appendix 3, present the emission sources and indicate a reduction of approximately 95% in emissions under the sustainable system. However, it is worth noting that the sustainable system described by Nab and Maslin (2020) involves the complete replacement of chemical fertilizers with organic residues, which would likely jeopardize the maintenance of current production volumes in Brazilian coffee farming.

In this regard, more feasible alternatives involve production systems that incorporate good agricultural practices while maintaining Brazil's competitive production levels. Examples of such practices include: shaded coffee systems; intercropping coffee with *Brachiaria* grass or legumes; organic production systems; use of more productive and pest-resistant cultivars; integrated pest and disease management; efficient coffee drying processes; efficient irrigation systems; water reuse in processing; and balanced crop nutrition (Consórcio Pesquisa Café, 2021). Each of these practices entails specific costs and benefits that must be estimated.

On the cost side, two main components can be identified. The first relates to the implementation of sustainable practices aimed at reducing emissions and enhancing carbon sequestration in the soil. In this regard, it is worth noting that GHG emissions from coffee production can be mitigated through a variety of conservation-oriented farming practices—such as intercropping coffee with cover crops (Guerra *et al*., 2021), incorporating pruning residues into the soil (Cerri *et. al*., 2017), and applying organomineral fertilizers or compost (Matos and Pizzol, 2022). These practices, collectively referred to as conservation coffee farming, comprise a range of soil management strategies designed to increase the accumulation of green and residual biomass, as discussed by Anis *et. al*. (2022). The cited authors associate such practices with relatively low implementation costs.

However, in addition to those previously mentioned, there is a second cost component stemming from the process of measurement, reporting, and verification of the carbon balance required for credit certification. This certification-related cost is significant and is typically considered a transaction cost, which includes a substantial fixed component for each carbon credit project. In this regard, concerning the certification of carbon credits in Brazil's agricultural sector for the voluntary market, Vargas et. al. (2022, p. 13) point out that "soil carbon monitoring projects, for instance, involve high costs and consequently hinder the participation of small and medium-sized rural producers in the market."

It is also worth highlighting the study by Oliveira Junior et. al. (2022), which conducted carbon balance assessments of coffee farms and demonstrated that carbon sequestration exceeded emissions in their case studies. Therefore, the potential carbon credits available for trade refer only to the certified additional carbon sequestration resulting from the adoption of improved agricultural practices—that is, only the marginal (additional) reduction is considered.

To support GHG emission reductions in coffee farming, the potential costs associated with adopting a sustainable production system—linked to carbon sequestration—were assessed based on the estimated impact of cultivating coffee intercropped with *Brachiaria* grass and the cost of contracting specialized technical assistance. The additional average cost of adopting the coffee cultivation system with *Brachiaria* intercropping was R$ 270 per hectare per year, according to the Embrapa Social Balance Report (Embrapa, 2022) and the corresponding Impact Assessment Report (Embrapa, 2022a).

The cost of contracting specialized technical assistance was estimated at R$ 204 per hectare, equivalent to two hours of service provided by an agronomist, based on the

Professional Fees Table for Agronomist Engineers[9] (SMEA, 2020). Such technical assistance is considered relevant due to the need for guidance on the adoption of good agricultural practices, which can be implemented without incurring significant additional input costs.

Based on these components, and to represent a modal scenario for coffee production, the total cost of adopting the production system required to offset 7.58 tons[10] of carbon dioxide equivalent per hectare ($tCO_2eq\ ha^{-1}$)—including variable certification costs incurred by the coffee producer[11]—was estimated at R$ 1,474 per hectare per year. The breakdown of variable costs is presented in Table A.2, Appendix 2. Due to the uncertainty of these projections and simulations of a new institutional environment, this study ignored other costs that were not actually disbursed in order to simplify the analysis.

In an effort to reduce the uncertainty related to transaction costs and the benefits of carbon credit sales, three projections of annual fixed costs were developed based on three sources: the study by Vargas et. al. (2022a) and publicly available price lists from two international certification entities[12]—Gold Standard (2022) and the EBC (2022).

- ✓ Cost 1 projection considered half of the average cost based on the three sources;
- ✓ Cost 2 projection was based on the average cost; and
- ✓ Cost 3 projection applied twice the average cost, based on the prices from the aforementioned sources.

5. Results and Discussion

The three projections of fixed certification costs and the three projected carbon credit prices in a regulated market are presented in Table 1.

The lowest annual fixed cost projection was R$ 31,229, the median cost was R$ 62,457, and the highest cost reached R$ 124,914 per year. A detailed breakdown of the median fixed cost is provided in Table A.2 in Appendix 2 of this article. These costs refer exclusively to transaction-related expenses and include only the certification fees for carbon credits in a specific coffee farm project. As previously mentioned, Vargas et. al. (2022) point out that the process of credit certification involves significant costs, particularly due to the application of Measurement, Reporting, and Verification (MRV) methods.

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[9] Professional Fees Table for Agronomist Engineers – HP SMEA, replaces the Table of Fees registered in CREA-MG, under No. 02/89.
[10] According to Cecafé and Imaflora (2022), the carbon balance (emissions minus sequestration) showed that good agricultural practices effectively increased carbon stocks by 7.58 $tCO_2eq\ ha^{-1}$ of green coffee compared to conventional practices.
[11] A variable certification cost of R$ 1,000 per hectare was assumed. The European Biochar Certificate (EBC) publishes a price list indicating a consulting package of 20 hours priced at EUR 3,000.
[12] Gold Standard and European Biochar Certificate (EBC).

The three projections of the average carbon credit price, estimated based on historical prices from the Carbon Emissions Futures, by Intercontinental Exchange (ICE), through Monte Carlo simulations, were R$ 246, R$ 262, and R$ 277. These projections reflect a scenario in which a Brazilian regulated carbon market would be integrated with other international markets, such as the European Union Emissions Trading System (EU ETS).

Table 1. Projections of certification costs and carbon credit prices.

Projection	**Cost 1**	**Cost 2**	**Cost 3**
Fixed Certification Costs (in R$ / year)	31,229	62,457	124,914
Projection	**Price 1**	**Price 2**	**Price 3**
Carbon Credit Price (in R$)	246	262	277

Source: research findings.

Consolidating these estimates, based on the combinations of the three fixed cost projections and the three average carbon credit price projections, it was possible to identify the minimum viable areas for coffee growers to engage in carbon credit trading, as presented in Table 2. The results show that, under the least favorable scenario for carbon credit trading, the minimum coffee farm size—on a property adopting sustainable agricultural practices, promoting carbon sequestration, and selling its credits—is 320 hectares. In other words, carbon credit trading exclusively from the coffee farm would only be attractive to the producer if the farm exceeded 320 hectares, as indicated by the scenario with the highest annual costs (Cost 3) and the lowest credit price (Price 1). In the most favorable scenario for carbon credit trading, which considers the lowest annual costs (Cost 1) and the highest credit price (Price 3), the minimum viable farm size for carbon credit commercialization would be 50 hectares.

Table 2. Scenarios of Minimum Viable Areas for Carbon Credit Trading in Coffee Farming.

Minimum Viable Area (hectares)			
	Cost 1	**Cost 2**	**Cost 3**
Price 1	80	160	320
Price 2	61	122	244

Price 3	50	100	200

Source: research findings.

The costs and revenues of the median scenario (Cost 2 and Price 2) are graphically presented for a hypothetical property with 200 hectares of coffee cultivation suitable for carbon sequestration through good agricultural practices in Figure 1. It is worth noting that the 200-hectare farm size was chosen to exemplify a situation in which the carbon trading activity reaches a viable scale. Subsequent analyses will be conducted to indicate the percentage of properties, based on data from the 2017 Agricultural Census by IBGE (2019), that meet the estimated minimum viability scales.

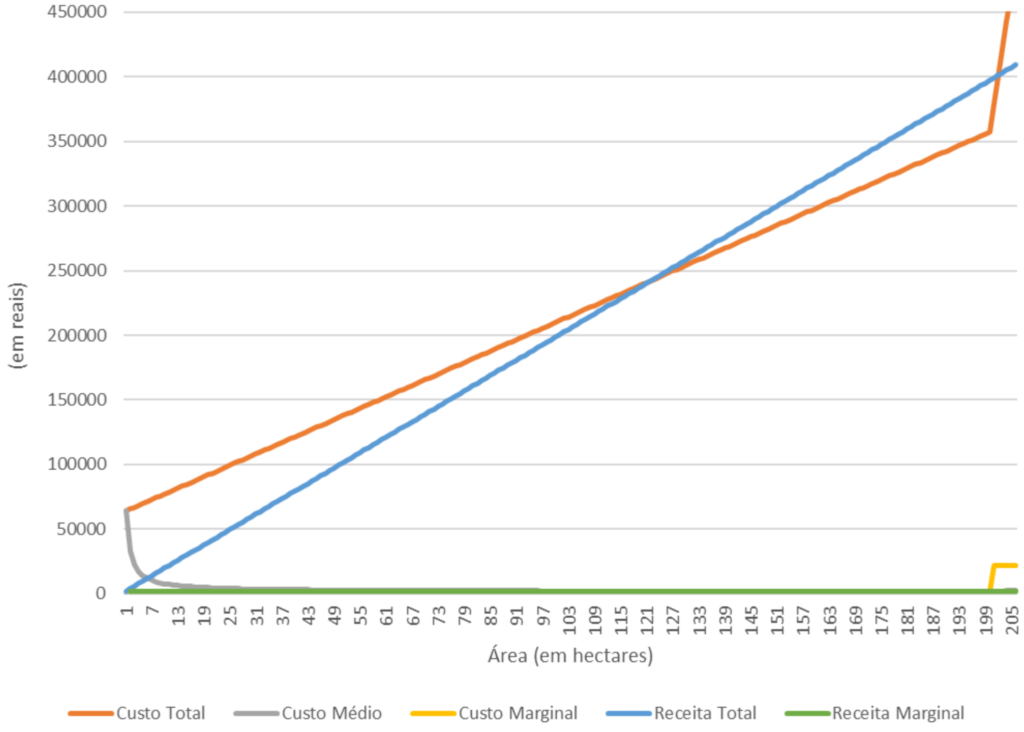
Figure 1 displays the Total Cost, Average Cost, Marginal Cost, Total Revenue, and Marginal Revenue curves, considering one year of activity. In this hypothetical scenario, it is possible to observe that from 122 hectares onward, Total Revenue exceeds Total Cost, indicating financial viability according to the break-even price method. The behavior of each curve in Figure 1 is derived from the following data:

- Total Cost, which sums the Fixed Certification Cost of R$ 31,229 and a Variable Cost of R$ 1,474, as previously mentioned and detailed in Appendix 2, is graphically represented by a line with an intercept at R$ 31,229 and increases by R$ 1,474 per hectare;

- Marginal Cost is constant, represented by a horizontal line at R$ 1,474 per hectare until the entire area suitable for carbon sequestration is reached; after this point, which in the current example is 200 hectares, the Marginal Cost increases proportionally to the cost of establishing new coffee plantation areas per hectare. It is noteworthy that the product level was standardized per hectare, considering a carbon credit of 7.58 $tCO_2eq\ ha^{-1}$, i.e., the marginal production cost of R$ 1,474 corresponds to producing 7.58 tCO_2eq per hectare of cultivation;

- The Average Cost curve, resulting from dividing Total Cost by hectares, decreases at a decreasing rate until the entire suitable area for carbon sequestration is reached; during this phase, economies of scale are observed as the Fixed Cost is spread over the product level, which in this study is measured per hectare. Beyond 200 hectares, Average Cost increases proportionally to the cost of establishing new plantation areas.

Figure 1. Costs and revenues from carbon credit trading on a 200-hectare coffee farm under the Cost 2 × Price 2 scenario.



Source: research findings.

- Total Revenue is represented by an upward-sloping line intercepting the origin, increasing by approximately R$ 1,986 per hectare, as this is the revenue generated by 7.58 tCO_2eq per hectare at Price 2, estimated at R$ 262 per tCO_2eq;
- Accordingly, Marginal Revenue, resulting from dividing Total Revenue by hectare, coincides with the slope of the Total Revenue line, i.e., R$ 1,986. Its graphical representation is a horizontal line.

Essentially, it should be emphasized that, in the simulation performed, increasing returns to scale were observed due to the decreasing Average Cost up to the size of the coffee farm suitable for carbon sequestration, which in this case was 200 hectares. When the carbon credit production potential is reached across the entire suitable coffee cultivation area, the Marginal Cost exhibits a jump equivalent to the expansion cost of one additional hectare of coffee farm. For this example, a cost of R$ 20,000 per expanded hectare was assumed, corresponding approximately to the minimum establishment costs for coffee farming. This cost is roughly the average production cost reported by Conab for the years 2022 and 2023 across 10 coffee-growing regions (CONAB, 2024).

Thus, beyond the production scale of 200 hectares, Total Cost surpasses Total Revenue again, and similarly, Marginal Cost exceeds Marginal Revenue, indicating that the profit maximization point has been exceeded. Therefore, in the analyzed scenario, 200 hectares would be used for carbon sequestration, generating an annual profit of R$ 39,935. Under this more favorable scenario, properties larger than 200 hectares tend to achieve even higher profits than estimated (R$ 39,935 per year), as the activity exhibits economies of scale, with decreasing Average Cost until the area suitable for GHG reduction is reached.

Based on the simulation that demonstrated the financial viability of selling carbon credits from a 200-hectare coffee plantation, it is important to highlight that only 2% of coffee-producing establishments in Brazil have areas of this size or larger, according to the 2017 Agricultural Census (IBGE, 2019). Extending the analysis beyond this hypothetical 200-hectare example, under the baseline scenario (Cost 2 × Price 2)—in which the minimum viable area for carbon credit commercialization is 122 hectares—fewer than 5% of coffee-producing establishments would meet the required scale. However, data from IBGE (2019) also indicate that these top 5% of producers account for approximately 39% of the country's total coffee-harvested area.

In the most favorable scenario—characterized by the lowest certification costs and the highest projected credit prices (Cost 1 × Price 3)—the minimum viable farm size falls to 50 hectares. Under this scenario, and considering the land structure of the coffee sector reported in the 2017 Agricultural Census, a regulated carbon cap-and-trade policy could potentially cover up to 52% of Brazil's total harvested coffee area, involving up to 12% of producing establishments.

Finally, in the least favorable scenario for carbon credit trading (Cost 3 × Price 1), in which the minimum viable farm size for carbon credit commercialization would be 320 hectares, a regulated cap-and-trade carbon market policy would potentially cover fewer than 2% of coffee-producing establishments. These producers account for 14% of the total coffee-harvested area in Brazil[13], based on data from IBGE (2019), presented in Appendix 1.

6. Considerations on the Carbon Market Instrument for the Coffee Sector

It is important to emphasize that the results of this exploratory study were based on projected carbon credit prices, which are subject to high volatility. Carbon prices fluctuate in both voluntary and regulated markets due to the interaction of economic factors (supply and demand), regulatory, policy, and technological changes, as well as the level of confidence in offset and emission reduction mechanisms.

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[13] The Agricultural Census does not provide the exact number of producers with farms of 320 hectares or more. Instead, its area classifications follow the stratification outlined in Appendix 1. Producers with at least 320 hectares fall within the census area brackets of 200–500 hectares, which correspond to 2% and 1% of establishments, respectively. These two groups are responsible for 27% and 14% of the total harvested area.

Economic growth, energy demand, and the number of available allowances primarily affect carbon credit prices in regulated markets. For instance, when analyzing the European Union Emissions Trading System (EU ETS), the findings of Dong *et al*. (2022) showed that the outbreak of the COVID-19 pandemic led to a significant drop in carbon prices. However, with the introduction of the EUR 750 billion green recovery plan, the carbon market gradually stabilized, and carbon prices began to rise.

To mitigate the uncertainty surrounding these price trends, this study considered different scenarios, including higher and lower prices, calculated based on the standard deviation observed between 2012 and 2022. Nevertheless, future carbon prices may not follow the same pattern as those observed during the analyzed period.

Similarly, the certification costs of carbon credits and the costs of mitigating GHG emissions in coffee farming may differ from the projections presented in this article. Certification costs may vary depending on the certifying bodies authorized to operate in this market, while GHG mitigation costs are expected to differ according to the emission factors of each farm, which are shaped by specific soil, climate, and technological conditions. Even so, the results obtained based on currently available information provide highly relevant insights to support decision-making regarding the implementation of a carbon market, both by policymakers and the coffee sector.

Therefore, based on the data used in this study, a prospective cost-effectiveness analysis of the carbon market—specifically for the coffee sector—points to a relatively low level of participation among coffee farms, in percentage terms. The benefit-cost ratio suggests that integration into the carbon market is only economically viable for farms with significantly large production scales, in terms of harvested area, especially when compared to the landholding structure of Brazilian coffee farming.

For this analysis, based on Perman et al. (2003), transaction costs were incorporated into the cost comparisons, which indeed affected the assessment of the cost-effectiveness of the carbon market in coffee farming. In summary, the transaction costs related to the certification of carbon credits by coffee producers represent the main barrier to achieving a positive benefit-cost ratio for farms smaller than 50 hectares—the minimum area estimated in the most favorable scenario. It is worth emphasizing that, in an intermediate scenario, such costs would prevent the participation of coffee farms smaller than 122 hectares in a cap-and-trade policy.

Additionally, from the perspective of equity within the carbon market, the findings of this study suggest negative implications of this instrument for income distribution in the coffee sector, based on a "business-as-usual" scenario. In other words, if the high certification costs persist and carbon prices follow the trends observed in major regulated markets, the sale of carbon credits in coffee farming will only be attractive to large-scale producers, potentially leading to a concentration of income.

Therefore, it is essential that the design of the Brazilian Emissions Reduction Market include institutional mechanisms aimed at reducing certification costs. Based on the options discussed by Cacho et al. (2013), previously cited, it is advisable, for instance, to allow certification processes to be carried out by coffee grower cooperatives. Through aggregation, cooperatives can increase production scale by combining the cultivated areas of their members, enabling cost-sharing.

In addition, implementation and monitoring methodologies can be developed through agricultural research and technological innovation—for example, lower-cost carbon balance methodologies. Such technological advances may help reduce the expenses associated with Measurement, Reporting, and Verification (MRV) processes, which are intrinsic to certification.

7. Conclusion

The prospective scenarios explored in this study indicate that, within the framework of a regulated carbon market under a cap-and-trade system, the minimum financial viability scale for the commercialization of carbon credits from coffee production is relatively high when compared to the scale of nearly all coffee farms in the country. Notably, the significant disparity in the minimum viable areas can be attributed to changes in projected costs. These costs—particularly the fixed certification costs, treated here as transaction costs—would render carbon credit commercialization unfeasible for at least 88% of coffee-producing establishments. Nonetheless, if mechanisms are adopted to reduce such transaction costs, the regulation of the carbon market is likely to be implemented in a more socially inclusive manner, promoting regional development along with increased and more equitable income distribution.

Therefore, further research is needed on how to implement a regulated carbon market in Brazil. Nonetheless, it is important to emphasize the need for institutional mechanisms to mitigate certification costs—such as enabling carbon credit certification processes to be carried out by coffee grower cooperatives. Additionally, agricultural research and innovation should be supported to develop lower-cost carbon accounting methodologies, thereby increasing the feasibility of certification processes. Such recommendations may contribute to the long-term sustainability of Brazilian coffee by facilitating its access to the carbon market.

Although this prospective study provides inputs for the design of a public cap-and-trade policy, its results do not offer a comprehensive feasibility assessment of carbon trading for specific coffee farms, given the heterogeneity of Brazil's coffee sector. It is worth noting that both emission factors and the costs of adopting sustainable practices vary according to the soil and climate conditions of each farm. Studies that apply this method to specific production systems within a given coffee-producing region are likely to yield more accurate results regarding the feasibility of carbon credit trading from coffee production. Each farm, therefore, may have its own potential for generating carbon credits depending on its edaphoclimatic and technological conditions—based on Measurement, Reporting, and Verification (MRV) methods for carbon credits that are still pending regulatory definition.

Considering the uncertainty surrounding carbon credit prices, which can fluctuate significantly and behave differently from the assumptions made in this study, this exploratory research can be further enhanced by updating parameters and data as the institutional framework of the cap-and-trade system consolidates in Brazil’s regulated carbon market. The scenarios may also be refined by incorporating analyses of the variable costs involved in adopting good agricultural practices and their potential to enhance carbon sequestration in coffee plantations. Finally, complementary estimates could be made regarding potential gains for coffee growers from carbon credits generated by forested areas within their rural properties. In this context, a broad scope for future research emerges, which can contribute substantially to the sustainable development of Brazilian agriculture.

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Appendix 1

Table A.1. Distribution of coffee farms and coffee-growing area by farm size category – 2017 IBGE Agricultural Census.

	Number of farms	%[14]	Area	%[15]
More than 0 to less than 0.1 ha	164	100%	159	100%
From 0.1 to less than 0.2 ha	178	100%	102	100%
From 0.2 to less than 0.5 ha	1,662	100%	464	100%
From 0.5 to less than 1 ha	5,242	99%	2,347	100%
From 1 to less than 2 ha	17,141	97%	13,797	100%
From 2 to less than 3 ha	21,575	91%	27,597	99%
From 3 to less than 4 ha	20,700	83%	38,840	97%
From 4 to less than 5 ha	21,815	75%	48,122	95%
From 5 to less than 10 ha	54,601	67%	154,408	92%
From 10 to less than 20 ha	47,807	46%	200,441	82%
From 20 to less than 50 ha	42,710	28%	293,136	70%
From 50 to less than 100 ha	17,442	12%	208,345	52%
From 100 to less than 200 ha	7,840	5%	195,437	39%
From 200 to less than 500 ha	4,002	2%	211,793	27%
From 500 to less than 1,000 ha	978	1%	105,002	14%
From 1,000 to less than 2,500 ha	363	0%	73,576	7%
2,500 to less than 10,000 ha	105	0%	39,496	3%
10,000 ha and more	9		4,141	0%
Producers without area	27		63	
TOTAL	264,361	100	1,617,293	100

Source: IBGE (2019) and research findings.

14 Cumulative percentage by number of farms with different sizes in descending order.
15 Cumulative percentage by farm area with different sizes in descending order.

Appendix 2

Table A.2. Breakdown of fixed and variable costs.

Cost description	**Value (in R$)**	**Source**
Fixed Costs		
Carbon credit certification (per project)	62,457	Study presented in Vargas et. al. and public price tables by two international certifiers: Gold Standard (GOLD STANDARD, 2022) and European Biochar Certificate (EBC, 2022). The average of the three values was considered, converted at the August 2022 exchange rate, as follows. Vargas et. al. (2022a) – R$90,875 (project development, validation and monitoring); Gold Standard (2022) – R$38,375 (annual registry account fee, preliminary certification review fees, project design certification review fees, performance certification review fees); EBC (2022) – R$58,122 (registration fee, seal fee, technical pre-audit, sample collector training and analyses).
Variable Costs		
Soil management (per hectare)	270	Value of inputs and labor for soil management based on adoption of coffee cultivation system with intercropping with *Brachiaria* grass, according to Embrapa Social Balance (EMBRAPA, 2022) and respective Impact Assessment Report (EMBRAPA, 2022a).
Specialized Technical Assistance (per hectare)	204	Equivalent to two technical hours of an agronomist engineer, according to the Professional Fees Table for Agronomist Engineers (SMEA, 2020).
Carbon credit certification (per hectare)	1,000	Amount referring to a part of the 20-hour consultancy package (EUR 3,000) from the certifier European Biochar Certificate (EBC). It was considered that the 20-hour package would suffice for a farm of approximately 15 hectares.

Source: research findings.

Appendix 3

Table A.3. GHG emissions in coffee cultivation.

Emission source	**CO_2 Emission ($kg\ CO_{2e}\ kg^{-1}$) Conventional agriculture**	**CO_2 Emission ($kg\ CO_{2e}\ kg^{-1}$) Sustainable agriculture**
Fertilizer	0.96	0.01
Fossil fuels	0.03	0.03
Electricity	0.01	0.01
Pesticides	0.01	0.00
Total	1.01	0.05

Source: Nab and Maslin (2020).