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The Potential of Brazilian Agriculture for Reducing Greenhouse Gases: An Analysis of Coffee Growing and Lessons for COP30

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Summary

This article analyzes the potential of Brazilian coffee production to contribute to national greenhouse gas (GHG) mitigation targets under the recently established Brazilian Emissions Trading System (SBCE). The methodology uses a scenario analysis, based on census data, to assess how transaction costs determine a minimum viable area for market participation, impacting the sector's aggregate potential. The results reveal a critical duality: although there is a vast theoretical mitigation potential, estimated at 13 million tons of CO_2eq, its realization is severely limited by economic barriers that could prevent up to 67% of this total from being realized. The high costs of certifying and monitoring carbon credits exclude most coffee growers, especially family farmers, which constitute the structural foundation of the sector. We conclude that the effectiveness of the carbon market as a climate policy in Brazil depends on institutional innovations—such as collective certification through cooperatives and the development of low-cost monitoring technologies—to reduce transaction costs. Additionally, it is recommended that voluntary instruments, such as carbon-neutral coffee labeling, be promoted to encourage the adoption of good agricultural practices in an inclusive manner and achieve Brazil's GHG reduction targets. Such measures are crucial to ensuring broad and equitable participation of rural producers, aligning the market instrument with the reality of national agriculture.

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Resumo
Este artigo analisa o potencial da cafeicultura brasileira para contribuir com as metas nacionais de mitigação de gases de efeito estufa (GEE) no âmbito do recém-estabelecido Sistema Brasileiro de Comércio de Emissões (SBCE). A metodologia utiliza uma análise de cenários, baseada em dados censitários, para avaliar como os custos de transação determinam uma área mínima viável para a participação no mercado, impactando o potencial agregado do setor. Os resultados revelam uma dualidade crítica: embora exista um vasto potencial teórico de mitigação, estimado em 13 milhões de toneladas de CO_2eq, sua efetivação é severamente limitada por barreiras econômicas que podem impedir a realização de até 67% desse total. Os altos custos de certificação e monitoramento dos créditos de carbono excluem a maioria dos cafeicultores, especialmente os agricultores familiares, que constituem a base estrutural do setor. Conclui-se que a eficácia do mercado de carbono como política climática no Brasil depende de inovações institucionais, como a certificação coletiva via cooperativas e o desenvolvimento de tecnologias de monitoramento de baixo custo, para reduzir os custos de transação. Adicionalmente, recomenda-se que instrumentos voluntários, como a rotulagem de café carbono neutro, sejam promovidos para incentivar a adoção de boas práticas agrícolas de forma inclusiva e atingir as metas de redução de GEE do Brasil. Tais medidas são cruciais para assegurar a participação ampla e equitativa dos produtores rurais, alinhando o instrumento de mercado à realidade da agricultura nacional.

Palavras-chave: Mitigação de GEE; Mercado de Carbono; Agricultura de Baixo Carbono; Custos de Transação; Cafeicultura.

1. Introduction

Addressing climate change has established itself as one of the most pressing challenges of our time, mobilizing the international community to seek solutions to mitigate the rise in the planet's average temperature. In this context, Brazil has made ambitious commitments, setting targets to reduce its greenhouse gas (GHG) emissions by 48% by 2025 and 53% by 2030, compared to 2005 levels, and to achieve net emissions neutrality by 2050. To operationalize these targets, Law 15.042/2024 established the Brazilian Greenhouse Gas Emissions Trading System (SBCE), a regulated carbon market that serves as the country's main climate policy instrument (BRASIL, 2024).

The SBCE follows the global trend of expanding carbon pricing, with 80 instruments covering approximately 28% of global emissions by early 2025, according to the World Bank (2025). This expansion is notable in large middle-income economies, such as Brazil. International experience with these markets, which generated more than

USD 100 billion in 2024, offers lessons for the implementation and improvement of the Brazilian system.

The agricultural sector emerges as a central player in this strategy, displaying a dual nature. On the one hand, it represents a significant source of emissions, accounting for 27.2% of Brazil's total GHG emissions in 2014 (Freitas et al., 2016). On the other, it is recognized as a provider of mitigation solutions. The SBCE legislation itself explicitly includes "more efficient agricultural and livestock systems" and the "increase of carbon stocks in agricultural soils and pastures" as eligible sources for generating carbon credits, positioning the sector not only as a target of regulation but also as a provider of environmental solutions.

To investigate the dynamics and challenges of this integration, this study adopts Brazilian coffee farming as an in-depth case study. This choice is justified by the sector's relevance, as Brazil is the largest coffee producer and exporter and the second-largest consumer of this beverage in the world. According to Conab – National Supply Company (2025), Brazil's 2024 coffee harvest was 54.2 million 60-kg bags, from an area of 1.88 million hectares, with an average productivity of 28.8 bags per hectare. In monetary terms, the Gross Value of Coffee Production in 2024 was estimated at R$78.2 billion (Brazil, 2025). Regarding coffee growers, it is worth noting that the country has more than 264,000 coffee-producing establishments in 1,448 municipalities, with 78% of these coffee farms considered family-owned (IBGE, 2019).

The central research problem lies in the hypothesis that, although the theoretical mitigation potential of coffee farming is significant, its implementation is threatened by economic barriers intrinsic to the functioning of carbon markets. The high transaction costs associated with the certification, monitoring, reporting, and verification (MRV) of credits create a minimum scale of economic viability that can, in practice, exclude most producers from the market. Therefore, the objective of this article is to quantify the impact of this scale barrier on the global effectiveness of the carbon market for the agricultural sector and discuss the implications for designing a climate policy that is both environmentally effective and socially inclusive.

2. Fundamentals of Agriculture's Contribution to GHG Emissions and Mitigation

The agricultural sector's participation in climate mitigation strategies is a global and national imperative. In June 2023, Decree 11.550/2023 was enacted, establishing guidelines for the development of Sectoral Climate Change Mitigation Plans (BRASIL, 2023). These Sectoral Plans cover several sectors listed in the National Climate Change Policy (PNMC), including the agricultural sector. This sector plays a prominent role in any strategy to mitigate the causes of climate change. As Freitas et al. (2016) rightly point out, the release of greenhouse gases (GHG) from agriculture reached 423.1 million tons of CO_2eq in 2014, representing 27.2% of the country's total emissions.

In Brazil, agricultural efforts are formalized through policies such as the Sectoral Plan for Consolidating a Low-Carbon Economy in Agriculture (Plano ABC+), which aims to promote the adoption of sustainable technologies and production practices. Launched for the 2020-2030 decade, it succeeds and expands the previous plan (2010-2020), consolidating an approach that integrates GHG mitigation, climate adaptation, and productivity gains. The plan is the embodiment of climate policy for the sector that holds one of the greatest potential contributions to national goals.

Agriculture can contribute to GHG reduction in two main ways: by reducing direct emissions (e.g., through animal manure management or the optimized use of nitrogen fertilizers) and by removing carbon dioxide (CO_2) from the atmosphere, sequestering it in biomass and, primarily, in the soil. Table 1 presents quantitative area targets for the adoption of technologies that reduce GHG emissions, as covered by the ABC+ Plan.

Table 1. Quantitative Targets of the ABC+ Plan (2020-2030) by Technology

Technology (SPSABC)	**Adoption Target (Area/Volume/Unit)**
Practices for the Recovery of Degraded Pastures (PRPD)	30 million hectares
Direct Grain Planting System (SPDG)	12.5 million hectares
Crop-Livestock-Forest Integration Systems (iLPF)	10 million hectares
Bioinputs (including FBN)	13 million hectares
Planted Forests (FP)	4 million hectares
Irrigated Systems (IS)	3 million hectares
Agroforestry Systems (SAFs)	100 thousand hectares

Animal Production Waste Management (MRPA)	208.4 million m^3 of treated waste
Intensive Termination (IT)	5 million animals slaughtered

Source: Brazil (2021).

Technologies such as no-till farming, integrated crop-livestock-forestry (iLPF) and other intercropping, the restoration of degraded pastures, and agroforestry systems, mentioned in the ABC+ Plan, are recognized for their potential to increase soil carbon stocks. This is an ecosystem service that can be quantified and promoted through environmental policies.

Thus, the formulation of public and private policies focused on sustainability has become a priority. In this context, economic and voluntary environmental policy instruments emerge as complementary alternatives to traditional command-and-control mechanisms by promoting market incentives and incentives for the adoption of sustainable practices. The next two sections present the fundamentals of the carbon market through the tradable permit system and the fundamentals of carbon-neutral labeling as a voluntary environmental policy instrument.

2.1. The Tradable License System as an Economic Instrument of Environmental Policy

The tradable permit system is an environmental policy instrument in which a regulatory agency issues permits representing degradation/pollution quotas corresponding to a specific maximum degradation/pollution threshold for a given geographic area. After the initial distribution and/or sale among polluting/degrading agents in that region, it is possible and recommended to negotiate these permits among these agents. This method of controlling aggregate levels of environmental degradation allows for the establishment of a feasible physical limit for pollution/degradation and a total number of permits or quotas equivalent to the assimilative, carrying, and/or sustainable capacity of the environment.

According to Sterner and Coria (2012), this environmental policy instrument establishes property rights related to the right to pollute or degrade the environment and helps remove the externalities implicit in the absence of property rights or the environment's "public good" character. Thus, creating a market, with a price mechanism, to trade the right to generate externalities reduces their adverse effects.

Theoretically, this system promotes cost-effectiveness, as the reduction effort is allocated where the cost is lowest, in line with the equimarginal principle (Baranzini et al., 2017). The success of the instrument, however, depends on well-defined property rights, rigorous monitoring, and a competitive market (Schmalensee; Stavins, 2017; Sterner; Coria, 2012).

Although the tradable license system is recognized for its theoretical cost-effectiveness, in achieving reduction targets at the lowest aggregate cost (Perman et al., 2003), its practical application is challenged by transaction costs, which can alter the cost-effectiveness ranking of the instruments.

Furthermore, as pioneered by Coase (1937), the magnitude of transaction costs can make or break the functioning of a market. This assertion could even compromise the effectiveness of an environmental policy based on tradable licenses.

Thus, in the case under study – the insertion of coffee farming into the carbon market – transaction costs, especially those related to carbon credit certification, are relatively significant (Santos; Nogueira, 2025). A comparative study of transaction costs in carbon offset projects by Cacho et al. (2013) indicated the unfeasibility of smaller-scale projects in terms of productive area. Thus, these authors highlight the need to reduce transaction costs to make smaller-scale projects viable and, to this end, suggest three strategies: a. carrying out collective projects to share costs; b. utilizing existing infrastructure/management capacity; and c. reducing information costs, especially through implementation and monitoring methodologies (Cacho et al., 2013).

The issue of feasibility scale raises another relevant evaluation criterion: equity. This criterion seeks to identify how the costs and benefits of the environmental management policy instrument are distributed. Assessing this aspect is important because maximizing the benefit/cost ratio can lead to social injustice, causing the less privileged segments of society to bear the costs and receive few benefits. In this context, it is also necessary to choose the perspective from which equity will be sought, which can be weighted by the criteria of equality, ability to pay, favoring the less privileged, competitive conditions, among others. Finally, equity in a policy can also be sought from a spatial/geographical perspective by reducing regional disparities.

2.2. Labeling as a Voluntary Instrument of Environmental Policy

Voluntary environmental policy instruments are mechanisms to encourage the adoption of sustainable practices that do not require direct state coercion. In contrast to command-and-control instruments, which impose legal obligations, voluntary instruments rely on the spontaneous participation of companies and producers, stimulated by market pressures, reputation, economic incentives, and the pursuit of environmental differentiation (SEGERSON, 2013; CASTRO, 2006).

According to Segerson (2013), the effectiveness of these approaches depends on three fundamental conditions: (i) sufficiently strong participation incentives so that the benefits outweigh the costs of the obligations assumed; (ii) adequate monitoring to ensure voluntary compliance; and (iii) mechanisms that reduce free-riding behavior among participants in collective programs. In the context of carbon-neutral coffee labeling, these conditions are essential, as the success of certification depends both on the credibility of the audit and on consumers' perception of the added environmental value.

In terms of economic efficiency, voluntary instruments tend to have lower administrative costs and greater flexibility in implementation, as they allow agents to adjust their mitigation strategies according to their production realities (Segerson; Li, 1999). However, the OECD (2003) emphasizes that the effectiveness of these approaches is generally limited, as they rarely incorporate mechanisms that equalize marginal reduction costs among producers. This means that, in the case of coffee farming, small farms may face proportionally higher fixed audit and compliance costs, which reduces the attractiveness of individual certification.

The motivation for adopting voluntary instruments is associated with both market and institutional factors. According to Castro (2006), companies and producers can adopt proactive stances aimed at reducing costs, accessing new markets, obtaining price premiums or financing, and improving their corporate image. In the case of carbon-neutral labeling, adoption can be explained by the growing consumer demand for products with a lower carbon footprint and the possibility of adding economic and reputational value to certified coffee.

However, Segerson (2013) warns that significant environmental improvements are less likely in contexts of weak political will for mandatory policies, since voluntary participation is limited to those who perceive positive net benefits. Thus, there is a trade-off between rigor and adherence: more demanding requirements tend to reduce the participation rate, even if they increase the environmental credibility of the seal.

Additionally, Segerson (2013) notes that certification and labeling programs function as signaling instruments, reducing information asymmetry between producers and consumers. Thus, carbon-neutral labeling reflects an effort to convert environmental benefits—public goods—into tradable private goods (Prakash, 2000), internalizing positive externalities related to emissions mitigation. This dynamic reinforces the role of environmental certification as a hybrid instrument between environmental policy and market strategy.

Environmental labeling functions as a market mechanism to mitigate information asymmetry, a classic problem in agricultural products whose sustainability attributes are "credence goods", as their quality cannot be verified by the consumer. In the absence of a credible signal, quality uncertainty can harm high-standard producers, as predicted by Akerlof (1970). Third-party certification acts as a costly and effective signal (Stiglitz, 1987), allowing producers to reliably communicate their practices, correct this market failure, and justify a price premium (Caswell; Mojduszka, 1996). In the coffee sector, these sustainability standards help structure the market and create value (Giovannucci; Ponte, 2005).

Finally, it is worth noting that voluntary, performance-based approaches—such as carbon-neutral certification—tend to be more effective than those based on specific practices, as they allow flexibility in choosing emission reduction methods and encourage technological innovation (Segerson, 2013). This characteristic is particularly relevant in coffee farming, where soil, climate, and technological conditions vary widely between regions and producers.

In short, carbon-neutral coffee labeling can be interpreted as a concrete application of voluntary environmental policy instruments. Its effectiveness depends on the credibility of the audit, the reduction of compliance costs for small producers, and the existence of market incentives that guarantee economic and reputational returns proportional to environmental effort.

2.3. Transaction Costs and the Viability Scale Barrier

Despite the theoretical elegance of tradable allowance markets, their practical application is conditioned by the existence of transaction costs, a concept pioneered by Coase (1937). In the context of carbon markets, these costs manifest as the expenses required to define, validate, monitor, and trade carbon credit. They include the high costs of developing methodologies, third-party validation, continuous monitoring of adopted practices, and periodic verification of mitigation results.

These costs have a particular economic characteristic: a significant portion of them is fixed, meaning they do not vary proportionally with the scale of the project. The administrative expense to certify credits for a 10-hectare property can be very similar to that for a 500-hectare property. This dynamic creates an inevitable consequence: the existence of a minimum scale for economic viability. Small-scale projects that generate a small volume of carbon credits may become financially unviable, as the potential revenue from the sale of credits is insufficient to cover the high fixed transaction costs.

This phenomenon transforms a theoretically neutral market instrument into a mechanism that, in practice, selects participants based on their scale. The study by Santos and Nogueira (2025) estimates that, for Brazilian coffee production, this minimum viable area is between 50 and 320 hectares, a threshold that excludes most producers. The literature suggests strategies to mitigate this barrier, such as aggregating small producers into collective projects, using existing management infrastructure (such as cooperatives), and reducing information costs through simplified implementation and monitoring methodologies, as suggested by Cacho. et al. (2013).

Reducing certification costs through collective projects is a common practice in the voluntary sustainability labeling process, which is part of voluntary environmental policy instruments. This certification has established itself as one of the main instruments for encouraging the adoption of environmentally responsible agricultural practices in Brazilian coffee production (Moreira et al., 2011). In addition to differentiating the product in specialized markets, certification can serve as a mechanism to motivate the adoption of good environmental practices, including measures aimed at reducing environmental impact, rational management of natural resources, and valuing rural labor (Duarte; Ferreira, 2019; Pereira, 2014).

For small producers, individual certification faces significant economic barriers, particularly due to fixed audit and compliance costs (Duarte; Ferreira, 2019). However, in the Brazilian context, collective certification through cooperatives emerges as the main strategy to overcome this barrier. In this model, the fixed audit and compliance costs, which make individual certification unfeasible (Duarte; Ferreira, 2019), are distributed among members, generating economies of scale that enable the participation of small producers (Latynskiy; Berger, 2017). Initiatives such as Certifica Minas Café demonstrate that this approach is a strategic path toward sustainable coffee production, by making the process accessible and strengthening local governance (Minas Gerais, 2020; Perosa; Sparsis , 2016; Araújo et al., 2016).

Thus, for a coffee grower with approximately 10 hectares, sustainable certification is viable and strategic when implemented collectively. Group certification reduces fixed costs, improves environmental management capacity, and promotes competitive insertion in differentiated markets, consolidating its position as an instrument for sustainable rural development and mitigation of agricultural emissions.

3. Analytical Approach to Mitigation Potential

The methodology adopted in this study is a scenario-based quantitative forecasting approach designed to assess the impact of different carbon market configurations on the aggregate potential for greenhouse gas (GHG) mitigation and revenue generation in Brazilian coffee production. The approach goes beyond a simple potential estimate, structuring itself as an analytical framework to investigate how the critical variable of transaction costs—embodied in different levels of minimum economic viability—determines the environmental effectiveness and social equity of the Brazilian Emissions Trading System (SBCE). The methodological design was conceived to test the central hypothesis of the study: that the effectiveness of a market instrument is not intrinsic, but rather a direct function of the institutional design that supports it, especially regarding its ability to include or exclude small producers who form the basis of the national agricultural sector.

3.1. Modeling Fundamentals and Data Sources

The empirical analysis is based on the integration of two primary data sources, whose combination allows for the isolation and quantification of the effect of the scale barrier. The deliberate choice to separate the characterization of the sector's agrarian structure from environmental and economic impact parameters constitutes the foundation of the methodological strategy, allowing for an accurate assessment of the gap between the total theoretical potential and the potential that can actually be mobilized under different market conditions.

The structural basis for the analysis comes from the 2017 Agricultural Census, conducted by the Brazilian Institute of Geography and Statistics (IBGE). This data source offers a detailed and granular portrait of the national coffee industry, providing the universe of rural establishments and their precise distribution by area strata. The use of this data is crucial because it allows us to quantify, for each scenario, the share of the total area and the number of producers that would be eligible or excluded from the carbon market, revealing the magnitude of the impact of the entry barrier.

The technical and economic coefficients that parameterize the model were extracted from the prospective study by Santos and Nogueira (2025). This research provides the essential estimates for modeling, namely:

GHG Mitigation Potential: The average emission reduction coefficient per hectare, expressed in tons of carbon dioxide equivalent (tCO_2eq), achievable with the adoption of a portfolio of low-carbon agricultural practices in coffee production. According to Cecafé and Imaflora (2022), the carbon balance (emissions minus sequestration) showed that good agricultural practices effectively increased carbon stocks by 7.58 tCO2eq ha-1 of green coffee compared to conventional practices. Thus, to calculate the GHG reduction potential, the minimum viable area for each scenario was multiplied by 7.58.

Revenue Generation Potential: The estimated revenue per hectare (in R$/ha) from the sale of generated carbon credits. This value incorporates assumptions about the market price of carbon and the conversion rate of mitigation potential into tradable credits. This study considered the amount of R$ 277 per carbon credit, which corresponds to the most optimistic projection (Quote 3) by Santos and Nogueira (2025). Thus, to calculate the revenue generation potential, the viable area of each scenario was multiplied by the average emission reduction coefficient per hectare (7.58) and also by 277.

A central assumption of the model is the homogeneity of these coefficients across different production scales and even across different regions. It is assumed that the mitigation potential and revenue per hectare are constant, regardless of property size and soil and climate conditions. While recognizing that, in reality, variations in productivity and efficiency may exist, this simplification is a necessary methodological decision to enable the analysis. It allows for the analytical isolation of the effect of the scale barrier imposed by transaction costs, which is the central focus of this research, preventing the results from being confounded by other variables.

It is important to emphasize that the analysis is based on the technical and economic coefficients of Santos and Nogueira (2025), whose methodology already incorporates a robust sensitivity analysis to address carbon market uncertainties. The authors do not limit themselves to a single value, but construct nine scenarios based on the combination of three projections of fixed certification costs (low, medium, and high) and three carbon credit price projections. This approach reveals a spectrum of results in which the minimum area required to enable market participation varies considerably, ranging from 50 hectares in the most optimistic scenario (low costs and high prices) to 320 hectares in the most pessimistic (high costs and low prices).

Despite this variation, the fundamental conclusion remains consistent across all scenarios: the commercialization of carbon credits is economically unviable for the vast majority of coffee growers, since even the most favorable scenario (50 ha) still excludes 88% of the country's producers (Santos; Nogueira, 2025). This finding lends greater solidity to the central hypothesis of this work. Thus, the methodology allows us to clearly measure how much of the mitigation potential is lost solely due to market design.

3.2. Construction of Economic Feasibility Scenarios

The scenarios analyzed should not be interpreted as predictions, but rather as simulations of different public policy and market environments. Each minimum viable area threshold (10, 50, 100, and 200 hectares) serves as a proxy for the level of success of institutions in mitigating transaction costs, as per the theoretical discussion presented in Section 2. The transition between scenarios, from the most optimistic to the most restrictive, directly reflects the consequences of different regulatory choices, illustrating the trade-off between the microeconomic efficiency of individual projects and the macroenvironmental effectiveness and social inclusion of the policy as a whole.

<u>Scenario 1:</u> Optimistic (10-hectare limit) – Broad Inclusion via Institutional Innovation This new scenario represents the theoretical maximum mitigation potential

that could be achieved under a highly effective and inclusive climate policy framework. It models a reality in which transaction costs have been drastically reduced, making participation in the carbon market economically viable even for small-scale family farms. The plausibility of this scenario is anchored in two institutional innovations discussed in the article's theoretical framework: Aggregation via Collective Action: Based on the strategies proposed by Cacho et al. (2013), this scenario presupposes the widespread adoption of "programmatic" or "aggregated" projects, in which cooperatives and producer associations act as intermediaries. By consolidating thousands of small properties into a single project, the high fixed costs of developing methodology, certification, and MRV (Monitoring, Reporting, and Verification) are distributed among all participants, drastically reducing the cost per producer and per hectare.

Market Incentives via Voluntary Instruments: In line with the discussion on environmental labeling, this scenario also assumes the consolidation of voluntary markets for carbon-neutral products. Obtaining a price premium through labels such as "carbon-neutral coffee" generates an additional source of revenue for small producers. This market incentive, as theorized by Segerson (2013), not only helps cover residual compliance costs but also strengthens the attractiveness of participation, transforming GHG mitigation from a burden into a value-adding opportunity.

<u>Scenario 2:</u> Moderate (50-hectare limit) – Partial Inclusion This scenario reflects a market environment where partial progress has been made in reducing transaction costs, but barriers remain significant for most smallholder farmers. It corresponds to the lower viability limit estimated by Santos and Nogueira (2025) and simulates a reality in which some cooperative structures are able to participate or where MRV technologies have become more accessible, but not yet sufficient to engage the base of the production pyramid.

<u>Scenario 3:</u> Restrictive (100-hectare limit) – Structural Exclusion This scenario models the implementation of a conventional carbon market, or "business-as-usual," in which transaction costs remain high and there are no institutional mechanisms to support the aggregation of small projects. The market operates under a logic of pure microeconomic efficiency, favoring medium- to large-scale properties that have the capital and technical capacity to absorb these costs. It represents a failure of policy to

adapt to the structural reality of Brazilian agriculture, characterized by the predominance of family farming.

Scenario 4: Highly Restrictive (200-hectare limit) – Elite Market This scenario simulates a market with prohibitive entry barriers, where only the largest and most capitalized agricultural companies can participate. It illustrates the most extreme outcome of a poorly designed policy, in which the market instrument serves a minimal fraction of the sector, resulting in marginal environmental effectiveness and maximizing social exclusion and income concentration.

By framing the scenarios in this way, the analysis demonstrates that the level of mitigation achieved by the SBCE is not a predetermined outcome, but a direct consequence of the policy choices made during its design phase. The substantial difference in outcomes between the 10-ha and 200-ha scenarios quantifies the opportunity cost—both environmental and social—of opting for an exclusionary path over an inclusive one. The "Optimistic" scenario therefore establishes a crucial analytical benchmark, defining maximum potential. The gap between this benchmark and the other scenarios can be conceptualized as the "Mitigation and Equity Gap": the sum of the unrealized climate benefit and the rural development opportunity lost due to persistently high transaction costs.

3.3. Scope of Analysis and Levels of Geographic Aggregation

To capture both the aggregate and distributional consequences of the different feasibility scenarios, the study employs a multilevel analysis. This approach allows for a deeper and more nuanced understanding of the policy's impacts, revealing dynamics that would remain hidden in a single-level analysis.

National Level: The primary objective of national-scale analysis is to quantify the macro-impact of policy design. It measures the overall environmental effectiveness of the carbon market in each scenario, calculating the aggregate GHG mitigation and revenue potential. More importantly, this level measures the full magnitude of the "Mitigation and Equity Gap," answering the central question: "How much of the total national potential is effectively realized or lost due to the scale barrier?"

Municipal Level: The analysis is then expanded to the municipal scale, a deliberate methodological choice to investigate the spatial heterogeneity of impacts. A national average alone would mask critical local dynamics, since the agrarian structure—the ratio of family to large-scale farming—varies drastically across Brazil's different coffee-growing regions. This subnational analysis was designed to expose how the exclusionary effects of transaction costs can exacerbate existing regional inequalities. It demonstrates how a seemingly neutral national policy (by establishing a single eligibility criterion by area) can, in practice, generate a geography of "carbon oases"—municipalities with a predominance of large farms that benefit from the market—and "carbon deserts"—municipalities dominated by family farming that are completely marginalized. This approach directly connects the economic instrument to issues of distributive justice and regional development, reinforcing the need to consider the equity criterion in the design of environmental policies, as discussed in Section 2.1. To ensure the relevance of the analysis, the selection of municipalities for the case study focused on the 28 municipalities that make up the 99.5th quantile of the total area cultivated with coffee in Brazil, ensuring that the investigation focuses on the most significant production centers in the country.

4. Mitigation Potential of Coffee Growing: Results and Discussion

The scenario analysis quantifies the vast mitigation potential of coffee farming and, at the same time, reveals how different environmental policy instruments determine its implementation. The results demonstrate that, while the regulated carbon market (SBCE) faces structural barriers that limit participation, voluntary instruments such as environmental labeling emerge as a strategic way to include family farming and maximize the sector's climate and social impact.

4.1. National Aggregate Potential

The national-scale analysis, presented in Table 1, contrasts two distinct policy models. The 50-, 100-, and 200-hectare scenarios, projected by Santos and Nogueira (2025), simulate the likely outcomes of the SBCE, where transaction costs for the sale of carbon credits create scale barriers. In contrast, the inclusive 10-hectare scenario was specifically inserted to estimate the maximum potential that could be achieved through a policy encouraging the labeling of "carbon-neutral coffee," for example. This voluntary instrument, rather than relying on the sale of credits, creates value through a price premium in the consumer market, making the adoption of sustainable practices viable even for small producers, especially when organized in cooperatives.

Table 1. National Mitigation Potential and Revenue from Carbon Credits from Coffee Farming under Different Feasibility Scenarios

Minimum viable scale (ha)	Area (ha)	Tons of GHG (tCO_2eq)	Revenue (R$)
10	1,717,654	13,019,817	-
50	1,093,251	8,286,843	2,295,455,395
100	823,909	6,245,230	1,729,928,771
200	567,951	4,305,069	1,192,503,997

Source: Prepared by the authors based on data from Santos and Nogueira (2025) and projection of inclusive area for inclusive scenario.

The data reveal a significant difference. The labeling scenario (10 ha) demonstrates that Brazilian coffee production has the technical potential to mitigate approximately 13 million tons of CO_2 equivalent (tCO_2eq). However, if climate policy is restricted to the carbon market (SBCE), even in its most optimistic configuration (50 ha), the realizable potential drops to 8.3 million tCO_2eq. In a more restrictive scenario (200 ha), which reflects the reality of high transaction costs, the potential plummets to 4.3 million tCO_2eq.

This means that a policy focused exclusively on the regulated market would fail to realize between 36% and 67% of the sector's total mitigation potential. The difference of nearly 8.7 million tCO_2eq between the labeling scenario and the more restrictive SBCE scenario represents the "opportunity cost" of not implementing a complementary policy to encourage voluntary instruments. It is clear that, for Brazil to achieve its climate goals, promoting labeling is not just an option, but a strategic necessity to engage the base of the production pyramid.

In this context, the results suggest that planning for this Brazilian Emissions Reduction Market under the *cap-and-trade system* should consider institutional means of reducing certification costs and allowing for the aggregation of the diffuse potential of small producers to maximize the policy's effectiveness. Based on the options presented by Cacho et al. (2013), it is recommended that these certification processes be conducted by coffee grower cooperatives that, through aggregation, increase the scale of production by combining the productive areas of their members, allowing for the sharing of these costs. It is worth mentioning that this practice of collective certification, through cooperatives, for example, has already been adopted for sustainable labeling certifications, considered voluntary environmental policy instruments.

Furthermore, implementation and monitoring methodologies can be developed through agricultural technology research, such as lower-cost carbon balance methodologies. This technological advancement can reduce Measurement, Reporting, and Verification (MRV) costs in the case of carbon credit trading, as well as sustainable labeling audit costs inherent to these certification processes, without compromising their international credibility.

4.2. Asymmetric Impacts at the Municipal Level

The municipal-level analysis deepens this conclusion, showing how a labeling policy could function as a powerful instrument for regional development, precisely in areas that would otherwise be marginalized by the carbon market. Tables 2, 3, and 4 expose the heterogeneity of impacts, where the local agrarian structure determines who wins and who loses.

Table 2. Potential area for adopting good practices that reduce GHG emissions per municipality in area ranges from 10, 50, 100 and 200 hectares.

Municipality	Property area from 10 hectares (in hectares)	Property area from 50 hectares (in hectares)	Property area from 100 hectares (in hectares)	Property area from 200 hectares (in hectares)
Patrocínio (MG)	25,326	17,883	10,866	2,235
Boa Esperança (MG)	18,804	15,444	12,363	7,275
Três Pontas (MG)	18,952	14,679	11,793	6,503
Campos Gerais (MG)	22,382	14,196	9,756	5,799
Piumhi (MG)	13,901	12,327	10,707	8,565

São Sebastião do Paraíso (MG)	15,399	12.117	9,377	5,949
Machado (MG)	12,775	10,472	7,279	3,955
Monte Carmelo (MG)	12,999	10,256	7,026	7,026
Garça (SP)	10,059	8,628	7,580	5,389
Ibiraci (MG)	12,664	8,319	5,078	2,078
Araguari (MG)	11,673	7,856	4,324	1,609
Linhares (ES)	14,737	7,839	4,282	1,797
Jaguaré (ES)	12,247	7,032	4,840	2,478
Campestre (MG)	12,954	6,665	4,772	3,598
Rio Bananal (ES)	15,905	5,874	2,606	589
São Mateus (ES)	11,408	5.205	3.019	1,644
Manhuaçu (MG)	12,969	4,928	1,660	1,660
Nova Venécia (ES)	10,334	4,341	1975	803
Carmo do Rio Claro (MG)	8,485	4,247	1983	-
Vila Valério (ES)	9,155	4.113	2,813	1904
Santa Margarida (MG)	7,933	3,780	2,789	1,334
Lajinha (MG)	6,972	3.261	1917	567
Afonso Cláudio (ES)	9,393	3.215	1,091	382
Pancas (ES)	8,823	3,069	1,578	594
Iúna (ES)	7,583	3,039	1,664	903
Simonésia (MG)	7,539	2.187	798	-
Castelo (ES)	7,411	1903	183	-
Nova Resende (MG)	9,027	1,892	775	-

Source: Prepared by the authors based on data from Santos and Nogueira (2025) and projection of inclusive area for inclusive scenario.
Note: The selection represents the 28 municipalities in the 99.5 quantile, which together account for 0.5% of the total area cultivated with coffee in Brazil.

This effect is evident at the municipal level, as illustrated in Table 3. The municipalities of Patrocínio (MG) and Carmo do Rio Claro (MG), for example, clearly illustrate the impacts that could occur if the regulated carbon market allows the participation of coffee farms with an area of 50 hectares or more, or, more restrictively, at least 200 hectares. In Patrocínio, the inclusion of farms with an area of 50 hectares or more would result in agricultural revenue of R$37.5 million and a reduction of 135,600 tons of CO_2 equivalent.

However, if eligibility is limited to properties with 200 hectares or more, these values plummet to R$4.7 million in revenue and only 16,900 tons of GHG reduction in the municipality of Patrocínio, indicating a significant loss of economic and environmental potential. In contrast, in the more inclusive scenario, which encourages GHG reductions on properties with 10 hectares or more, Patrocínio would have the potential to reduce 191,971 tCO_2eq.

Table 3. Quantity of GHG reduction by municipalities in area ranges from 10, 50, 100 and 200 hectares.

Municipality	**GHG reduction on properties from 10 hectares (in ton of CO_2eq)**	**GHG reduction on properties from 50 hectares (in ton of CO_2eq)**	**GHG reduction on properties from 100 hectares (in ton of CO_2eq)**	**GHG reduction on properties from 200 hectares (in ton of CO_2eq)**
Patrocínio (MG)	191,971	135,553	82,364	16,941
Boa Esperança (MG)	142,534	117,066	93,712	55,145
Três Pontas (MG)	143,656	111,267	89,391	49,293
Campos Gerais (MG)	169,656	107,606	73,950	43,956
Piumhi (MG)	105,370	93,439	81,159	64,923
São Sebastião do Paraíso (MG)	116,724	91,847	71,078	45,093
Machado (MG)	96,835	79,378	55,175	29,979
Monte Carmelo (MG)	98,532	77,740	53,257	53,257
Garça (SP)	76,247	65,400	57,456	40,849
Ibiraci (MG)	95,993	63,058	38,491	15,751

Araguari (MG)	88,481	59,548	32,776	12.196
Linhares (ES)	111,706	59,420	32,458	13,621
Jaguaré (ES)	92,832	53.303	36,687	18,783
Campestre (MG)	98.191	50,521	36,172	27,273
Rio Bananal (ES)	120,560	44,525	19,753	4,465
São Mateus (ES)	86,473	39,454	22,884	12,462
Manhuaçu (MG)	98,305	37,354	12,583	12,583
Nova Venécia (ES)	78,332	32,905	14,971	6,087
Carmo do Rio Claro (MG)	64,316	32,192	15,031	-
Vila Valério (ES)	69,395	31,177	21,323	14,432
Santa Margarida (MG)	60.132	28,652	21,141	10.112
Lajinha (MG)	52,848	24,718	14,531	4,298
Afonso Cláudio (ES)	71,199	24,370	8,270	2,896
Pancas (ES)	66,878	23,263	11,961	4,503
Iúna (ES)	57,479	23,036	12,613	6,845
Simonésia (MG)	57,146	16,577	6,049	-
Castelo (ES)	56,175	14,425	1,387	-
Nova Resende (MG)	68,425	14,341	5,875	-

Source: Prepared by the authors based on data from Santos and Nogueira (2025) and projection of inclusive area for inclusive scenario.
Note: The selection represents the 28 municipalities in the 99.5 quantile , which together account for 0.5% of the total area cultivated with coffee in Brazil.

Table 4. Potential revenue from the sale of carbon credits by municipalities in area ranges from 50, 100 and 200 hectares.

Municipality	Income on properties from 50 hectares (in R$)	Income on properties from 100 hectares (in R$)	Income on properties from 200 hectares (in R$)

Patrocínio (MG)	37,548,220	22,814,906	4,692,740
Boa Esperança (MG)	32,427,150	25,958,096	15,275,026
Três Pontas (MG)	30,820,910	24,761,290	13,654,089
Campos Gerais (MG)	29,806,774	20,484,282	12,175,928
Piumhi (MG)	25,882,508	22,481,060	17,983,588
São Sebastião do Paraíso (MG)	25,441,580	19,688,512	12,490,877
Machado (MG)	21,987,640	15,283,425	8,304,156
Monte Carmelo (MG)	21,534,112	14,752,211	14,752,211
Garça (SP)	18,115,866	15,915,423	11,315,068
Ibiraci (MG)	17,467,072	10,662,073	4,363,094
Araguari (MG)	16,494,929	9,078,930	3,378,353
Linhares (ES)	16,459,235	8,990,744	3,773,089
Jaguaré (ES)	14,764,809	10,162,354	5,202,958
Campestre (MG)	13,994,234	10,019,578	7,554,577
Rio Bananal (ES)	12,333,403	5,471,714	1,236,700
São Mateus (ES)	10,928,730	6,338,874	3,451,841
Manhuaçu (MG)	10,347,124	3,485,436	3,485,436
Nova Venécia (ES)	9,114,624	4,146,829	1,686,027
Carmo do Rio Claro (MG)	8,917,256	4,163,626	-
Vila Valério (ES)	8,635,902	5,906,344	3,997,753
Santa Margarida (MG)	7,936,715	5,855,952	2,800,947
Lajinha (MG)	6,846,992	4,025,048	1,190,507
Afonso Cláudio (ES)	6,750,407	2,290,729	802.070
Pancas (ES)	6,443,857	3,313,264	1,247,198
Iúna (ES)	6,380,867	3,493,834	1,895,993
Simonésia (MG)	4,591,957	1,675,529	-

Castelo (ES)	3,995,653	384,238	-
Nova Resende (MG)	3,972,557	1,627,237	-

Source: Prepared by the authors based on data from Santos and Nogueira (2025).
Note: The selection represents the 28 municipalities in the 99.5 quantile , which together account for 0.5% of the total area cultivated with coffee in Brazil.

Municipalities like Carmo do Rio Claro (MG), Nova Resende (MG), and Castelo (ES), where family farming is the backbone of the local economy, would have their mitigation potential completely eliminated under a restrictive SBCE scenario. However, these municipalities have significant potential under the 10-hectare scenario. In Carmo do Rio Claro, for example, a labeling policy could mobilize the mitigation of over 64,000 tCO_2eq, transforming what would otherwise be a "carbon desert" into a hub for sustainable coffee production and value-added value.

Labeling, therefore, not only has the potential to increase the total volume of mitigation but also to distribute it more equitably, generating economic and environmental benefits in regions that would otherwise be ignored by a market-based policy with high transaction costs. This reinforces the argument that promoting reduced certification costs is a tool for correcting market failures and promoting climate justice at the regional level.

4.3. Policy Implications and Recommendation: Integrating Regulated Market and Voluntary Incentives

The results converge to a clear conclusion: the design of climate policy for Brazilian agriculture should not be a choice between the regulated market (SBCE) and voluntary instruments (labeling), but rather a strategy of intelligent integration between both. The recommended integration between the regulated market (SBCE) and voluntary instruments (labeling) resonates with global efforts. The FAO (2023) advocates for True Cost Accounting (TCA) to uncover hidden costs in agriculture, which disproportionately affect smallholder producers.

The World Bank (2025) documents the expansion of ETSs like the SBCE, covering 28% of global emissions, but also points to the evolution and challenges of carbon credit markets. This study's results indicate that the SBCE, on its own, is an insufficient instrument for the reality of national coffee farming, as its transaction costs make it structurally exclusionary for 78% of producers. Relying solely on it for climate policy could result in low environmental effectiveness and a deepening of socioeconomic inequalities. Thus, a dual strategy, combining an accessible SBCE with credible voluntary labeling, aligns Brazil with global trends and the need to include the diverse actors and true costs of national agriculture in an effective and just climate policy.

The analysis of the 10-hectare scenario, however, is suggestive of the path forward. It demonstrates that the greatest mitigation potential lies precisely in the family farming segment on smaller properties, which can be mobilized by reducing certification costs.

Regarding labeling as a voluntary instrument, it is important to mention the dilemma of "premium erosion" and " mainstreaming ." The work of Giovannucci and Ponte (2005) warns that, as the supply of certified coffee increases and the practice becomes more common, the price differential compared to conventional coffee tends to decrease—a process known as *mainstreaming*. This phenomenon is also observed by Silva and Nonnenberg (2023), who highlight the reduction in premiums with the popularization of certification, although they do not use the term. This implies that the premiums observed today are not guaranteed in perpetuity, requiring certified producers to continually innovate and differentiate themselves to maintain their competitive advantage.

Therefore, it is recommended that an active public policy be implemented that promotes both "carbon-neutral coffee" labeling and other sustainability seals, as well as reducing MRV costs for generating carbon credits. Such a policy should include:

1. Support for Collective Certification: Promote and subsidize the structuring of cooperatives and associations so that they can manage group certification processes, dilute fixed costs and providing technical assistance to small producers.
2. Simplification and Credibility: Invest in research to develop low-cost Measurement, Reporting and Verification (MRV) protocols that maintain international credibility without placing a disproportionate burden on producers.
3. Valuation Campaigns: Develop marketing and awareness campaigns, both in the domestic and international markets, so that consumers recognize the added value of low-emission coffee, guaranteeing the price premium that makes the system viable.

By combining the economic instrument of the SBCE for large properties with the voluntary instrument created by labeling for small and medium-sized producers, Brazil can build a robust, effective climate policy aligned with its agricultural reality, transforming an environmental challenge into an opportunity for sustainable rural development.

5. Final Considerations

The analysis conducted in this study demonstrates that, although Brazilian coffee production has a GHG mitigation potential exceeding 13 million tons of CO_2eq, more than half of this potential is at risk of not being realized if the high transaction costs inherent in certification processes exclude small- and medium-scale producers. Implementing environmental policies to reduce GHG emissions without inclusive mechanisms can be environmentally ineffective, failing to mobilize the majority of the abatement potential, and socially exclusionary, concentrating the benefits on a limited number of large properties.

Furthermore, it should be recognized that the scenarios presented quantify the maximum mitigation potential, assuming that all eligible producers in each area would participate in the program. In practice, the adoption of low-carbon practices and participation in environmental markets are complex processes, influenced by a range of factors that transcend simple economic viability, such as access to technical assistance, credit availability, risk perception, and social capital.

Therefore, the actual adoption rate is likely below 100%, meaning that the constraint imposed by the feasibility threshold may actually be even greater than estimated. This limitation does not weaken, but rather strengthens the study's main conclusion: the urgency of active and well-designed public policies is even more critical to overcome not only economic barriers, but also information and capacity barriers that limit farmers' effective participation.

Given this diagnosis, the implementation of an active public policy that promotes both "carbon-neutral coffee" labeling and other sustainability seals, as well as the reduction of MRV costs for generating carbon credits, is crucial to aligning economic efficiency with environmental effectiveness and social equity. Based on the analysis and specialized literature, clear and actionable public policy recommendations emerge: a) It is recommended that SBCE regulation encourage and facilitate the creation of "aggregate" or "programmatic projects." b) The government should direct research and development resources, through research institutions such as Embrapa and universities, toward the creation of technologies that drastically reduce Monitoring, Reporting, and Verification (MRV) costs. c) Develop marketing and awareness campaigns, both domestically and internationally, so that consumers recognize the added value of low-emission coffee.

The transition to low-carbon agriculture is an opportunity for Brazil to reconcile its environmental, economic, and social objectives. However, for this opportunity to materialize, policy instruments must be designed for the realities of the Brazilian countryside , considering regional differences and tailored to each agricultural crop in our country. An inclusive and effective environmental policy will not emerge spontaneously. It needs to be built with an intelligent institutional architecture that recognizes and overcomes the barriers that currently impede the participation of the majority.

For future research, we suggest expanding the assessment of the adoption of good agricultural practices to reduce GHG emissions to other Brazilian agricultural crops, such as livestock and grain production. Additionally, further study is needed on the potential for adopting these practices through voluntary environmental policy instruments, with a focus on the marketing of products with a "carbon neutral" label.

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