Can Decentralized Incentive Schemes Induce Compliance with NDCs?

A Game Theoretic and Agent-based Modelling Analysis

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Abstract

Climate change necessitates urgent global action, particularly through coordinated policies that align environmental and economic goals. This study focuses on Brazil, a major emerging economy with a decentralized federative system, and proposes an innovative incentive scheme to motivate states to meet Nationally Determined Contributions (NDCs) using a mix of penalties ("sticks") and rewards ("carrots"). Addressing the key research question of whether a decentralized incentive-oriented scheme can effectively induce state compliance with emission targets, the study utilizes game theory and agent-based modeling (ABM) to develop and test the framework. Initial results indicate that tailored fiscal policies and incentive mechanisms can enhance state-level commitment to national and international climate goals. Furthermore, even under imperfect information, small fiscal policy can lead to NDC target achievement at state-level. This suggests that decentralized governance can be leveraged through fiscal policy for effective climate action.

Keywords

Fiscal Policy; Decentralized Incentive Scheme; Climate Change; Environmental Economic Policy; Greenhouse Gas Emissions; Mechanism Design; Agent Based Modelling.

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1. Introduction

Climate change, driven primarily by greenhouse gas emissions, has become one of the most pressing global challenges of our time. The increasing frequency and severity of extreme weather events underscore the urgent need for effective mitigation and adaptation strategies (Frame et al, 2020; Auffhammer, 2018; Kolstad and Moore, 2020). To address this, the international community has emphasized the importance of aligning environmental and economic policies, particularly through the management of externalities and common goods (Chander and Tulkens, 1997; Libecap, 2014; Verhoef, 1999; Zywicki, 1998). Given the transboundary nature of environmental issues, coordinated global action is essential, as unilateral efforts are often insufficient to achieve significant climate goals.

In response to these challenges, the Paris Agreement was adopted in 2015, introducing Nationally Determined Contributions (NDCs) as a mechanism for countries to set and commit to their own climate targets. Within this global framework, Brazil, a major emerging economy, faces unique challenges in meeting its NDCs due to its diverse environmental, economic, political, and social landscape. The Brazilian federative system, which grants substantial autonomy to its states, adds a layer of complexity to the implementation of cohesive national climate policies. This decentralized structure, however, also presents an opportunity to design innovative incentive mechanisms that leverage local dynamics to achieve broader environmental goals.

This paper aims to address these challenges by proposing an incentive scheme that employs both penalties ("sticks") and rewards ("carrots") to motivate Brazilian states to meet emission targets in a decentralized manner. By leveraging the country's federative structure, this approach seeks to harness the unique advantages of decentralized governance to fulfill national and international climate commitments. The objective of this study is to design an incentive scheme that leads countries to meet the NDCs in a decentralized manner using sticks and carrots. The main research question guiding this investigation is: Is it possible to design a mechanism to induce meeting the NDCs by means of a decentralized incentive-oriented scheme involving a neutral mix of tax and subsidies?

The literature review highlights several key gaps in current research. One significant gap concerns the utilization of fiscal policy as an incentive mechanism for subnational governments to comply with emission reduction targets. While extensive research has focused on national-level strategies and international agreements, there is a scarcity of studies addressing how fiscal tools can be tailored to subnational entities. This is particularly critical given that subnational governments hold significant regulatory power and can implement localized policies that contribute substantially to national and global emission reduction goals (Bennear and Stavins, 2007; Sterner and Coria, 2013). Additionally, the integration of agent-based modeling (ABM) to study the intersection of environmental and fiscal policy remains underexplored, despite its potential to provide valuable insights into the dynamics of decentralized governance structures (Farmer and Foley, 2009; Tesfatsion, 2002).

By examining these gaps, this paper aims to establish a comprehensive understanding of the current state of knowledge and identify the areas where further research is needed. The proposed incentive scheme will be developed using both theoretical and empirical approaches, including game theory and agent-based modeling, to ensure a robust and evidence-based framework. Ultimately, this study seeks to enhance cooperation and commitment to climate goals among Brazilian states through innovative fiscal policies and incentive mechanisms.

The structure of this study is as follows: Section 1 provides the introduction, outlining the study's context and objectives. Section 2 presents a comprehensive literature review, divided into three subsections: 2.1 explores the game-theoretic background relevant to environmental economics and fiscal policy, 2.2 discusses empirical studies utilizing agent-based modeling, and 2.3 identifies gaps in the existing literature. Section 3 details the methodology, including the theoretical model (3.1), the agent-based model (3.2), and the data and parameters used (3.3). Section 4 introduces the theoretical framework for the mechanism design problem, with subsections on complete information (4.1) and incomplete information with the tâtonnement strategy (4.2). Section 5 presents the initial empirical results, followed by a discussion of these results and the next steps in Section 6. Finally, Section 7 concludes the study, summarizing the findings and their implications for future research and policy development.

2. Literature Review

The increasing frequency and magnitude of extreme events, exacerbated by greenhouse gas emissions, underscore the substantial economic impacts these phenomena impose (Frame et al, 2020; Auffhammer, 2018; Kolstad and Moore, 2020). Addressing these challenges necessitates a coherent alignment between environmental and economic policies, particularly in the context of externalities and the management of common goods (Chander and Tulkens, 1997; Libecap, 2014; Verhoef, 1999; Zywicki, 1998). This complex interplay demands coordinated global action, as the transboundary nature of environmental issues renders unilateral efforts insufficient. Effective mitigation and adaptation strategies thus require collaboration at all levels of government and internationally to ensure climate change mitigation and adaption.

In response to this complex scenario, the Paris Agreement[4], adopted in 2015, introduced Nationally Determined Contributions (NDCs) as a mechanism for countries to set and commit to their own climate targets. Within this global framework, Brazil, as a major emerging economy, faces unique challenges in meeting its NDCs due to its diverse environmental, economic, political, and social landscape. This paper aims to address these challenges by designing an incentive scheme that employs both penalties ("sticks") and rewards ("carrots") to motivate Brazilian states to meet emission targets in a decentralized manner, leveraging the country's federative structure to meet the country's NDC.

The concept of using incentives to drive environmental policy compliance is well-documented in economic literature. However, the application of such schemes within a federative system, particularly in a country as vast and varied as Brazil, presents unique challenges and opportunities. This literature review will explore existing theoretical frameworks and empirical evidence related to decentralized environmental policies, the effectiveness of sticks and carrots in incentivizing compliance, and the specific hurdles associated with achieving NDC targets within the Brazilian context.

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[4] The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties during the UN Climate Change Conference (COP21) held in Paris, France, on December 12, 2015, and came into effect on November 4, 2016. The primary aim of the agreement is to limit the rise in global average temperature to well below 2°C above pre-industrial levels, with efforts to further restrict the increase to 1.5°C above pre-industrial levels. More details at: https://unfccc.int/process-and-meetings/the-paris-agreement.

By examining these areas, this review aims to establish a comprehensive understanding of the current state of knowledge, identify gaps that this study seeks to fill, and highlight the relevance and potential impact of the proposed incentive scheme. This foundation will support the development of a robust, evidence-based approach to enhancing cooperation and commitment to climate goals among Brazilian states through innovative incentive mechanisms.

2.1. Game-theoretic Background

Game theory, environmental economics, and fiscal policy intersect to provide a framework for analyzing and addressing complex environmental challenges. In environmental economics, game theory is utilized to model interactions between different agents, such as countries, corporations, or individuals, each with their own strategies and incentives (Hanley, Shogren, & White, 2013). This theoretical approach helps to predict and explain behaviors in scenarios like pollution control, resource management, and climate change mitigation. For instance, game theory can model the strategic behavior of countries in international climate agreements, illustrating how cooperation or non-cooperation can affect global emissions and climate outcomes (Barrett, 2003).

The problem of commons, such as the environment, has been significantly explored in game theory literature (Diekert, 2012; Ostrom, 1998). Garrett Hardin's essay "The Tragedy of the Commons" (1968) states that when benefits are concentrated and costs diffused, the optimal choice for individual agents will not be aligned with the optimal social choice. The author explores this concept within, what he coins, a "Prisoner's Dilema" where the socially optimal choice for each agent should be to not confess, however, due to strategic behavior, the result is not the socially optimal.

In the realm of fiscal policy, game theory is applied to design incentive mechanisms that can align individual or corporate behavior with societal environmental goals. Governments can use fiscal tools such as taxes, subsidies, or cap-and-trade systems to influence behavior (Pigou, 1932; Tietenberg, 2006). By applying game theory, policymakers can predict how these economic instruments will be perceived and acted upon by various stakeholders. For example, a carbon tax can be designed to ensure that companies internalize the external costs of their emissions, thereby reducing overall pollution (Nordhaus, 2008). Similarly, subsidies for renewable energy can incentivize investments in cleaner technologies (Borenstein, 2012).

Furthermore, game theory aids in the development of decentralized incentive schemes within environmental economics. Such schemes are critical for achieving Nationally Determined Contributions (NDCs) in climate policy (Ostrom, 2010). By considering the strategic interactions between federal and state governments or among countries, policymakers can create a balanced mix of "carrots and sticks" to encourage compliance with environmental regulations (Carraro & Siniscalco, 1993). This approach ensures that the benefits of cooperation and the costs of non-compliance are clearly defined, promoting more effective and sustainable environmental policies. In the Brazilian federative context, game theory can be instrumental in designing fiscal policies that incentivize states to adopt environmentally friendly practices while maintaining economic growth (Viola, Franchini, & Ribeiro, 2013).

2.2. Empirical Studies using Agent-Based Modelling

Agent-Based Models (ABMs) provide a robust framework for analyzing fiscal policy by simulating interactions of heterogeneous agents, capturing complex economic dynamics that traditional models often overlook. Fagiolo and Roventini (2012) demonstrate that ABMs can better incorporate non-linearities and agent heterogeneity, offering more realistic insights into fiscal policy impacts compared to DSGE models. Haber (2008) corroborates this by showing how ABMs can simulate both monetary and fiscal policies, emphasizing their ability to account for diverse agent behaviors and interactions.

Lamperti, Roventini, and Sani (2018) enhance the applicability of ABMs by using machine learning for model calibration, improving precision in policy analysis. LeBaron and Winker (2008) underscore the practical application of ABMs for economic policy advice, highlighting their capacity to manage complexity and heterogeneity inherent in economic systems. Castro et al. (2020) extend the discussion to climate-energy policy, illustrating ABMs' flexibility in modeling policy scenarios and agent responses, which is equally applicable to fiscal policies affecting energy markets.

These studies collectively emphasize the superiority of ABMs in capturing the dynamic and intricate nature of fiscal policy impacts, demonstrating their utility in designing effective and nuanced policy interventions. The incorporation of heterogeneous agent behaviors and advanced calibration techniques makes ABMs a valuable tool for policymakers aiming to understand and predict the outcomes of fiscal policies in a complex economic environment.

2.3. Gaps in the literature

One significant gap in the literature concerns the utilization of fiscal policy as an incentive mechanism for subnational governments to comply with emission reduction targets. While extensive research has focused on national-level strategies and international agreements, there is a paucity of studies addressing how fiscal tools can be tailored to subnational entities, such as states and municipalities, to incentivize compliance with environmental regulations. This gap is particularly critical given that subnational governments often hold significant regulatory power and can implement localized policies that can substantially contribute to national and global emission reduction goals. The current body of research largely overlooks the complexity of designing fiscal policies that account for the diverse economic conditions and political landscapes at the subnational level, thus highlighting the need for a more nuanced approach that integrates fiscal policy with environmental objectives (Bennear and Stavins, 2007; Sterner and Coria, 2013).

The integration of agent-based modeling (ABM) to study the intersection of environmental and fiscal policy is an emerging area with significant research gaps. ABM offers a powerful tool to simulate the interactions of heterogeneous agents, such as households, firms, and governments, within a complex system. However, its application to simultaneously address environmental outcomes and fiscal policies at subnational levels remains limited. Current models often focus on either environmental dynamics or fiscal mechanisms in isolation, lacking a comprehensive framework that captures their interplay. This gap is critical as ABM can provide valuable insights into how fiscal incentives influence agent behaviors and environmental outcomes, particularly in decentralized governance structures. Bridging this gap requires interdisciplinary approaches that combine economic theories, environmental science, and computational modeling to develop robust simulations that can inform policy-making (Farmer and Foley, 2009; Tesfatsion, 2002).

While substantial research exists on centralized approaches and international agreements for climate change mitigation (IPCC, 2014; UNFCCC, 2015), the specific role and effectiveness of decentralized instruments—such as regional carbon pricing, local subsidies for renewable energy, and state-level regulations—remain underexplored. This gap highlights the need for more empirical studies and theoretical analyses to understand how decentralized economic instruments can be effectively designed and implemented within federative systems to achieve

Nationally Determined Contributions (NDCs), accounting for the unique economic, political, and social contexts of subnational entities. Effective decentralized policies require careful calibration to align local incentives with broader national and international climate goals, ensuring that subnational actions contribute meaningfully to emission reduction targets (Ostrom, 2010; Aldy and Stavins, 2012).

3. Methodology

3.1. Theoretical Model

Initially, we develop a complete information model to examine decision-making at the individual state level, focusing on the conditions under which it would be optimal for a government to impose a carbon reduction incentive. We then explore a scenario without complete information, applying a tâtonnement approach to determine the optimal levels of taxes and subsidies. Subsequently, we extend our analysis to a game-theoretic framework. In this extended model, states derive their utility not only from their own decisions but also from the decisions made by other states. This approach allows us to capture the strategic interdependencies and anticipate the collective outcomes of state-level environmental decisions more effectively.

3.2. Agent-based model

While the model above provides useful insight into agent behavior under a decentralized economic instrument regarding emission target compliance, internalizing the tax and subsidy level with nonlinear solutions and the interaction between agent decision making is a difficult analytical task. To extract computational solutions, we adopt an agent-based simulation model.

In this design, there is an additional informational aspect where subnational governments influence one another not only directly in terms of emission level, but in adopting better practices. This behavior is aligned with existing literature on policy diffusion; The collective findings from the studies by Berry and Baybeck (2005), Case et al. (1993), Gomes (2014), Matisoff and Edwards (2014), Meseguer and Gilardi (2009), Shipan and Volden (2008), and Weaver (2020) provide robust evidence on the diffusion of fiscal policies among states.

Berry and Baybeck (2005) highlight how states use geographic information systems to study and respond to interstate competition, leading to the adoption of similar fiscal strategies to maintain competitiveness. Case et al. (1993) present empirical evidence that states' budgetary policies are significantly influenced by neighboring states' fiscal decisions, emphasizing the role of regional interdependence.

Gomes (2014) further supports these findings by illustrating how states learn from the fiscal successes and failures of their neighbors, leading to policy convergence over time. Matisoff and Edwards (2014) expand on this by showing that policy diffusion is not just a passive process but actively shaped by political, economic, and social factors within a region.

Meseguer and Gilardi (2009) focus on the mechanisms of policy diffusion, such as learning, competition, and coercion, demonstrating that states adopt policies based on the observed outcomes in other states. Shipan and Volden (2008) delve into the specific mechanisms of policy diffusion, identifying that learning and imitation are key drivers in the spread of fiscal policies.

Weaver (2020) adds to this by exploring how policy diffusion affects not only fiscal outcomes but also the political landscape, as states often adopt policies to align with the successful strategies of their neighbors, thereby reducing risks and uncertainties.

In summary, these studies collectively demonstrate that fiscal policies tend to diffuse geographically, with states influencing and adopting policies from their neighbors due to competitive pressures, observed successes, and regional economic interdependencies. This regional convergence leads to similar fiscal outcomes and strategies across neighboring states, reinforcing the interconnected nature of state fiscal policies.

3.3. Data and Parameters

The data used to calibrate the agent-based modelling is described in Table *1* - Data used and sources bellow.

Table 1 - Data used and sources

Parameter	Description	Source

Initial Level of Emission	Level of emissions per state in 2022.	Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa (SEEG)
Target Level of Emissions	Level of Emissions to be met in 2030 according to Brazil's NDC	Brazilian NDC, last updated in 2020.
Benefit: State level product	Gross Domestic Product per State in 2021.	Instituto Brasileiro de Pesquisa e Estatística (IBGE)
gamma: Carbon Price	Average value of unit of carbon in the regulatory European Union market.	Carbon Pricing Dashboard - World Bank
Gamma: Social Cost of Carbon	We use the authors' estimation on Brazil and the United States Environmental Protection Agency for projection of SCC	Ricke et al, 2019 and the United States Environmental Protection Agency (EPA)

Source: author elaboration

We also assume the following behaviors:

- Subnational governments take overall level of emissions into account, when deciding emission levels.
- Carbon Market Price behaves as a random walk, with average USD 5[5] per ton of carbon and standard deviation 2.
- Social Cost of Carbon will likely grow to USD 60 by 2030 per ton of carbon[6]. We assume the growth till go from the current USD 24 to USD 60 in a linear manner.

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[5] The price is an average of the carbon credit in voluntary carbon markets of the TSVCM Report, 2024 (available at: https://www.iif.com/tsvcm).

[6] Based on the EPA report "Social Cost of Greenhouse Gases", 2023, available at: https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf.

- Technology regarding emissions will growth at a 0.3% annual rate, like the Brazilian Total Factor Productivity[7]. This is a small rate seeing as how new productive technologies are emitting less[8].

4. Theoretical Framework: the mechanism design problem

The study uses a game-theoretic theoretic model to support the implementation of an Agent-Based Model to simulate different results. The theoretical model draws from a prisoner-dilemma framework to explore the decisions states will make in complying with the emissions cap imposed by federal government and how subsequently the federal government can adjust tax and subsidy to accelerate reaching the desired level of emissions (NDC commitment). The assumptions and concepts used in the model are described in *Table 2 - Assumptions in the Proposed Framework* bellow.

Table 2 - Assumptions in the Proposed Framework

Rationality: Subnational players are assumed to have bounded rationality and utility maximizing; i.e., subnational entities cannot internalize the social cost of carbon correctly. Central government has bounded rationality and utility maximizing; i.e., the central government will choose aggregate emission levels so that they comply with the NDCs. Notice that this is different that choosing emissions that are socially optimal (bounded rationality).
Information: Our initial model assumes perfect information, we then move on the imperfect information where the player's actions will depend on the level of fiscal policy enacted by the federal government and the decision of other players. For the empirical analysis we assume price

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[7] Please refer to IBRE/FGV for reference, available at: https://blogdoibre.fgv.br/posts/produtividade-total-dos-fatores-no-brasil-uma-visao-de-longo-prazo#:~:text=Nos%20anos%202000%20a%20PTF,PTF%20de%200%2C1%25%20a.a.

[8] This may be due to regulation (Porter and Linde, 1995; Albrizio et al, 2017; Ren et al, 2020) and efficiency gains (Popp, 2002; Wing, 2008).

uncertainty in all cases, but include additional elements of imperfect information throughout the different simulations.

Risk and uncertainty:
We assume risk regarding carbon market price behavior for all derivations of the model. We also include an extension of the model in the presence of imperfect information on state benefits.

Benefits:
All benefits derive from an increase in economic production and are directly correlated with the level of emissions. These benefits are contingent solely upon the individual emission levels. Benefits are considered strictly concave and increasing.

Costs:
The cost is perceived as the financial opportunity cost associated with emissions, which is equivalent to the potential revenue from selling emissions in a regulated carbon market. Costs encompass overall costs of emissions. Costs are considered strictly convex and increasing.

Intertemporal discount:
In our initial model, we do not consider there to be a discount rate between temporal realizations. As such, the game is time neutral.

Transaction costs:
We assume states can go from emitting to not emitting, and vice-versa, with no cost.

Technology (β):
Technology is assumed to be state-specific and exogenous and increasing over time.

Source: author elaboration.

4.1. Complete Information

4.1.1. The primitives of the model:

There are n states: $s_1, s_2, \dots, s_n$ and a national government G. There are several time periods, starting from $t = 0$.

At the initial time $t = 0$, there is no control of emissions, so that each state chooses its emission level according to its own interest, considering the economic benefits (larger GDP), the opportunity cost of emissions, measured as the unit cost of carbon sequestration credit in the world market, and the state's contribution to the environment cost of emissions.

The benefit function of state i at time t depends on that period's economic activity opportunities and is modelled as a strictly increasing, strictly concave function of the volume of emissions by state i at that period t, x_{it}:

$$b_{it}(x_{it})$$

The hypothesis that the function is increasing translates the idea that economic growth is associated with higher emissions. The hypothesis that it is concave translates decreasing marginal returns.

For the sake of illustration, we assume that the function takes the form below, where the parameter $\beta_{it} > 0$ reflects the state's overall emissions-generating technological-growth capacity at period t.

$$b_{it}(x_{it}) = \beta_{it} \ln{(x_{it})}$$

On the cost side, there is first an opportunity cost of emissions, which models the fact that carbon emissions reduction may be traded for money in international markets. That opportunity cost is modelled here as a linear function:

$$c_t(x_{it}) = \gamma_t x_{it}$$

The parameter $\gamma_t > 0$ is the per unit cost of carbon credits in the international market.

Additionally, state i understands that carbon emissions create an environment cost for the entire nation, when combined with all the states' emissions,

$$X_t = \sum_{j=1}^{n} x_{jt} = x_{it} + \sum_{j \neq i}^{n} x_{jt} = x_{it} + X_{-it}$$

That cost is cost is modelled as an increasing function which, for simplicity, we also assume linear:

$$C_t(X_t) = \Gamma_t X_t$$

Therefore, the total cost of emissions to state i is:

$$c_t(x_{it}) + C_t(X_{it}) = (\gamma_t + \Gamma_t)x_{it} + \Gamma_t X_{-it}$$

Hence, the net benefit of emissions in period t accrued to state i and he selects emission volume x_{it} is:

$$u_{it}(x_{it}; x_{-it}) = \tag{1}$$

$$b_{it}(x_{it}) - \left(c_t(x_{it}) + C_t(X_i)\right) = \beta_{it}\ln(x_{it}) - \left((\gamma_t + \Gamma_t)x_{it} + \Gamma_t X_{-it}\right)$$

4.1.2. The government's objective

The government aims to design a tax/subsidy legislation to be implemented in period 1 that should induce the states to coordinate a reduction in the countries' emissions by a specific percentual $\rho \in (0,1)$, for example a reduction in 10%, over the emissions level at $t = 0$.

The tax/subsidy scheme has the following format:

(i) Each state will be taxed according to the total volume of emissions it produced in period t, at tax rate τ.

(ii) Each state will receive a subsidy according to the total volume it is able to reduce in comparison to the previous year's emissions, at subsidy rate σ.

If the scheme generates the targeted reduction in a fiscally neutral manner, i.e., the total tax collected corresponds to the total subsidy paid, the mechanism is said G-sustainable, or sustainable for the national government.

Note that, by imposing such a mechanism to the states, G should also allow the states to internally design a similar tax/subsidy mechanism to be applied to subnational governments, the municipalities, or counties. Furthermore, the subnational governments should also be endowed with the power to impose a tax/subsidy scheme to their local constituents: the firms, the consumers, and all other agents who emit carbon locally.

Therefore, the proposed scheme takes full advantage of the main benefit of fiscal federalism, i.e., the fact that the closer a government is to the final beneficiaries of a public policy, the more efficient is its design (Oates, 1972; Musgrave, 1989; Rodden, 2004).

In what follows we focus on the relationship between the federal government and the states.

4.1.3. The emissions Nash equilibrium prior to the program's implementation

At period $t = 0$ the central government does not regulate emissions. Therefore, the states play a static game with each other where the resulting payoffs are given by (1):

$$u_{i0}(x_{i0}; x_{-i0}) = b_{i0}(x_{i0}) - \big(c_0(x_{i0}) + C_0(X_0)\big) = \beta_{i0} \ln(x_{i0}) - \big((\gamma_0 + \Gamma_0)x_{i0} + \Gamma_0 X_{-i0}\big)$$

The corresponding best responses are given by the first order conditions:

$$b'_{i0}(x_{i0}) = c'_0(x_{i0}) + C'_0(X_0), i = 1, \dots, n \tag{2}$$

The above equations express the optimal emissions choice of each state, conditional on the choices of the others.

Given the chosen parametrization, we have a dominant strategy Nash equilibrium:

$$\frac{\beta_{i0}}{x_{i0}} = \gamma_0 + \Gamma_0 \Leftrightarrow x_{i0} = \frac{\beta_{i0}}{\gamma_0 + \Gamma_0}$$

Therefore, the country's total volume of emissions in period 0 is given by the expression below, where $B_0 = \sum_{i=1}^{n} \beta_{i0}$:

$$X_0 = \sum_{j=1}^{n} x_{j0} = \frac{1}{\gamma_0 + \Gamma_0} \sum_{j=1}^{n} \beta_{j0} = \frac{1}{\gamma_0 + \Gamma_0} B_0 \tag{3}$$

4.1.4. The welfare maximizing carbon emission

For the sake of future comparison, let us calculate what would be the optimum aggregate volume of emissions.

The socially optimal emissions level if the solution to the following program:

$$\max_{x_{10},\ldots,x_{n0}} \sum_{i=1}^{n} u_{i0}(x_{i0}; x_{-i0}) = \sum_{i=1}^{n} \Big(b_{i0}(x_{i0}) - \big(c_0(x_{i0}) + C_0(X_0) \big) \Big)$$

This is a concave utility function. Therefore, the solution to this problem is the

$$\max_{x_{10},\ldots,x_{n0}} \sum_{i=1}^{n} \big(b_{i0}(x_{i0}) - c_0(x_{i0}) \big) + nC_0(X_0)$$

The solution comes from the FOC's:

$$b'_{i0}(x_{i0}) = c'_0(x_{i0}) + nC'_0(X_0), i = 1, \ldots, n \qquad (4)$$

Comparing the conditions (3) with (2), it is clear that the socially optimal solution puts higher weight on the social cost, increasing the right hand side and, thereby, reducing the emissions level of all states.

Given the chosen parametrization, we have a dominant strategy Nash equilibrium:

$$\frac{\beta_{i0}}{x_{i0}} = \gamma_0 + n\Gamma_0 \Leftrightarrow x_{SO_{i0}} = \frac{\beta_{i0}}{\gamma_0 + n\Gamma_0}$$

Therefore, the country's socially optimal total volume of emissions in period 0 is given by the expression below, where $B_0 = \sum_{i=1}^{n} \beta_{i0}$:

$$X_{SO_0} = \sum_{j=1}^{n} x_{j0} = \frac{1}{\gamma_0 + n\Gamma_0} \sum_{j=1}^{n} \beta_{j0}$$

$$X_{SO_0} = \frac{1}{\gamma_0 + n\Gamma_0} B_0 \qquad (5)$$

Thus, as expected,

$$x_{SO_{i0}} < x_{i0} \quad \text{and} \quad X_{SO_0} < X_0$$

A few comments are in order. Firstly, the aggregate environment cost function $C_0(X_0)$ only taken into consideration the negative environmental effect on the country, as if the country consisted of the entire world. This is clearly an approximation for the sake of simplification and could be easily extended to include the contributions of external countries this cost. Second, knowing what the socially optimal level of emissions would be, one could argue that the country would want to induce that volume to be reached. And this could indeed be the country's goal. However, our main interest is to make sure that the country can fulfill its emissions international commitments, rather than reaching the socially optimal solution. This study focuses on the country's original goal and only refer to the socially optimal for the sake of comparison.

4.1.5. The emissions Nash equilibrium after program implementation

At period $t = 1$ the emissions market is regulated by means of a (τ, σ) tax/subsidy mechanism.

Confronted with such a regulation, the states play a new emissions game where the new respective payoff are:

$$u_{it}(x_{it}; x_{-it}) = \tag{6}$$

$$b_{i1}(x_{i1}) - \big(c_1(x_{i1}) + C_1(X_i)\big) - \tau x_{i1} + \sigma(x_{i0} - x_{i1})$$
$$= \beta_{i1}\ln(x_{i1}) - \big((\gamma_1 + \Gamma_1)x_{i1} + \Gamma_1 X_{-i1}\big) - (\tau + \sigma)x_{i1}$$
$$+ \sigma x_{i0}$$

The corresponding best responses are still given by the first order conditions:

$$b'_{i0}(x_{i0}) = c'_0(x_{i0}) + C'_0(X_0) + (\tau + \sigma), i = 1, \dots, n \tag{7}$$

The above equations express the optimal emissions choice of each state, conditional on the choices of the others, in presence of the tax/subsidy regulation scheme.

Given the chosen parametrization, we have a dominant strategy Nash equilibrium:

$$\frac{\beta_{i1}}{x_{i1}} = \gamma_1 + \Gamma_1 + (\tau + \sigma) \Leftrightarrow x_{i1} = \frac{\beta_{i1}}{\gamma_1 + \Gamma_1 + (\tau + \sigma)}$$

Therefore, the country's total volume of emissions in period 1 is given by the expression below, where $B_1 = \sum_{i=1}^{n} \beta_{i1}$:

$$X_1 = \sum_{j=1}^{n} x_{j1} = \frac{1}{\gamma_1 + \Gamma_1 + (\tau + \sigma)} \sum_{j=1}^{n} \beta_{j1} = \frac{1}{\gamma_1 + \Gamma_1 + (\tau + \sigma)} B_1 \tag{8}$$

Note that the incentive effect of the regulation on the states' emissions (and the total volume of the country's emissions) is a function of the sum of the rates τ and σ. Therefore, for the sake of incentives, only the sum of the rates $T = \tau + \sigma$ matters. This property allows the government to choose a proper mix of tax and subsidy that yields a fiscally neutral policy, as will become clear next.

Furthermore, comparing (8) to (3) and (5) we can see the welfare maximizing potential of a Pigouvian tax scheme: if T is chosen such that:

$$\gamma_0 + n\Gamma_0 = \gamma_1 + \Gamma_1 + T \Leftrightarrow T = (\gamma_0 - \gamma_1) + (n\Gamma_0 - \Gamma_1)$$

Then the tax scheme induces the socially optimal emissions production.

In particular, if there are no changes in the parameters in period 2, then $\gamma_1 = \gamma_0$, $\Gamma_1 = \Gamma_0$, and the above condition becomes simply:

$$T = (n - 1)\Gamma_0$$

In other words, the tax policy forces each state to internalize the effect of its emissions on the other $n - 1$ states.

Although the tax policy could be used to gear towards the socially optimal emissions volume, the focus of the present study in rather to advice a country on how to make sure it complies with its NDCs commitments. This is explored next.

4.1.6. The central government complete information mechanism design problem

Suppose for the sake of future comparison, that the country's government observes all the relevant parameters of the economy and that, furthermore, it wants to design the regulation rule to induce the states decisions to aggregate to a total emission of:

$$X_1 = (1-\rho)X_0$$

In other words, there will be a reduction of 100ρ percentage of the volume of emissions in $t = 1$.

Then, from (3) and (8), using our parametrization, we must have:

$$X_1 = \frac{1}{\gamma_1 + \Gamma_1 + (\tau+\sigma)} B_1 = (1-\rho)X_0 = (1-\rho)\frac{1}{\gamma_0 + \Gamma_0} B_0$$

Equivalently,

$$(1-\rho)B_0[\gamma_1 + \Gamma_1 + (\tau+\sigma)] = [\gamma_0 + \Gamma_0]B_1$$

$$\tau + \sigma = \frac{\gamma_0 + \Gamma_0}{1-\rho}\frac{B_1}{B_0} - [\gamma_1 + \Gamma_1] \tag{9}$$

Suppose, for example, that there are no changes in the parameters of the economy from period 0 to period 1. Then, all parameters with subscripts 1 and 0 are the same. Therefore, equation (9) simplifies to:

$$\tau + \sigma = \frac{\rho}{1-\rho}[\gamma + \Gamma] \tag{10}$$

Where $\gamma = \gamma_0 = \gamma_1;\ \Gamma = \Gamma_0 = \Gamma_1$.

Suppose now that the central government wants to reach the reduced emissions in a fiscally neutral way.

Then, the tax and the subsidy rates must satisfy:

$$\tau X_1 = \sigma(X_0 - X_1)$$

The left-hand side of the equation is the central government's tax revenue. The right-hand side is the subsidy expenditure.

Therefore, it must be the case that:

$$\tau = \sigma \frac{X_0 - X_1}{X_1}$$

Now recall that $X_1 = (1-\rho)X_0$. Then,

$$\tau = \sigma \frac{X_0 - (1-\rho)X_0}{(1-\rho)X_0} = \sigma \frac{\rho X_0}{(1-\rho)X_0} = \sigma \frac{\rho}{1-\rho}$$

$$\tau = \sigma \frac{\rho}{1-\rho} \tag{11}$$

Thus,

$$\tau + \sigma = \sigma\left(\frac{\rho}{1-\rho} + 1\right) = \frac{1}{1-\rho}\sigma$$

From (9),

$$\frac{1}{1-\rho}\sigma = \frac{\gamma_0 + \Gamma_0}{1-\rho}\frac{B_1}{B_0} - [\gamma_1 + \Gamma_1] \Rightarrow \sigma = [\gamma_0 + \Gamma_0]\frac{B_1}{B_0} - (1-\rho)[\gamma_1 + \Gamma_1]$$

And, from (11),

$$\tau = \frac{\rho}{1-\rho}[\gamma_0 + \Gamma_0]\frac{B_1}{B_0} - \rho[\gamma_1 + \Gamma_1]$$

Therefore, the optimal tax/subsidy scheme that induces convergence at $t = 1$ to the country's NDCs which is fiscally neutral, is:

$$(\tau, \sigma) = \left(\frac{\rho}{1-\rho}[\gamma_0 + \Gamma_0]\frac{B_1}{B_0} - \rho[\gamma_1 + \Gamma_1], [\gamma_0 + \Gamma_0]\frac{B_1}{B_0} - (1-\rho)[\gamma_1 + \Gamma_1]\right) \tag{12}$$

Note that, if there are no parameter changes between the two periods, then,

$$\sigma = \rho[\gamma + \Gamma]$$

And,

$$\tau = \frac{\rho^2}{1-\rho}[\gamma + \Gamma]$$

Therefore, when there are no changes in the parameters between periods 0 and 1, the optimal tax/subsidy scheme that induces convergence at $t = 1$ to the emissions reduction the country committed to which is fiscally neutral, is:

$$(\tau, \sigma) = \left(\frac{\rho}{1-\rho}, 1\right)\rho[\gamma + \Gamma] \qquad (13)$$

4.2. The incomplete information case & the tatonnement strategy

4.2.1. The informational asymmetry

The previous section assumed that the central government could observe all parameters of that are relevant to the mechanism design. It is indeed reasonable to assume that the opportunity cost $c_t(x_{it}) = \gamma_t x_{it}$ is public knowledge and the environment cost function $C_t(X_t) = \Gamma_t X_t$ is calculable by all agents, including the federal government.

However, each state's benefit function $b_{it}(x_{it}) = \beta_{it}\ln(x_{it})$ is more probably its private information. There are several ways to model this information asymmetry.

In this section, we assume suppose that the true value of b_{it} is observable or verifiable with a lag, i.e., b_{i0} becomes public information at $t = 1$, b_{i1} becomes public information at $t = 2$, and so on, for $i = 1, \dots, n$.

Furthermore, the relationship between different time periods is given by:

$$b_{it} = b_{it-1} + \epsilon_{it}$$

where ϵ_{it} is a zero-mean random variable that is only observed by the state. Therefore, the benefit function at time t is:

$$b_{it}(x_{it}) = (\beta_{it-1} + \epsilon_{it})\ln(x_{it}) \qquad (14)$$

Where β_{it-1} is publicly observable at period t.

4.2.2. The central government problem under incomplete information

Now, the central government designs the incentive mechanism based on the expected values of the benefit functions. In period $t = 1$ the government knows $\beta_{io}, i = 1, \ldots, n$, but only knows the expected values of $\beta_{i1}, i = 1, \ldots, n$: $E_1[\beta_{i1}] = \beta_{i0}$.

The solution (8) is still the government solution where B_0 has not changed:

$$B_0 = \sum_{i=1}^{n} \beta_{i0}$$

But now B_1 is replaced with:

$$E[B_1] = E[\sum_{i=1}^{n} \beta_{i1}] = E[\sum_{i=1}^{n} (\beta_{i0} + \epsilon_{i1})] = \sum_{i=1}^{n} \beta_{i0} = B_0$$

Thus, the optimal (approximate) solution becomes:

$$(\tau_1, \sigma_1) = \left(\frac{\rho}{1-\rho}[\gamma_0 + \Gamma_0] - \rho[\gamma_1 + \Gamma_1], [\gamma_0 + \Gamma_0] - (1-\rho)[\gamma_1 + \Gamma_1]\right) \qquad (15)$$

Under this new approximate policy, basically three situations may arise, depending on the relationship the estimated value $E[B_1] = B_0$ and the true realized value of B_1.

The first one is the case where $B_1 = B_0$.

In that case the design is tuned to the country's economic situation and the optimal reduction is reached at once. The asymmetric information disappears when the coefficients are aggregated, and the country's government is able to implement the first best tax-subsidy policy.

The second one is the case where $B_1 > B_0$.

In that case both the tax and the subsidy rates that the government established in period 1 were underestimated and, therefore, low powered. The consequence is that there will not be enough emissions reduction in period 1, i.e., $X_1 > (1-\rho)X_0$.

The third one is the case where $B_1 < B_0$.

In that case both the tax and the subsidy rates that the government established in period 1 were overestimated and, therefore, too high powered. The consequence is that there will be too much emissions reduction in period 1, i.e., $X_1 < (1-\rho)X_0$.

Regardless of the potentially suboptimal outcome, the rule that express how the tax policy should be adjusted in each period remains the same, since $E_t[B_t] = B_{t-1}$. This, for $t \geq 1$ the period t tax-subsidy optimal policy is given by:

$$(\tau_t, \sigma_t) = \left(\frac{\rho}{1-\rho}[\gamma_{t-1} + \Gamma_{t-1}] - \rho[\gamma_t + \Gamma_t], [\gamma_{t-1} + \Gamma_{-1}] - (1-\rho)[\gamma_t + \Gamma_t]\right) \qquad (16)$$

Note that the policy will only be adjusted if there are changes in the parameters γ and/or Γ. In particular, if $\gamma_t = \gamma, \Gamma_t = \Gamma, \forall t > 0$, then,

$$(\tau_t, \sigma_t) = \left(\frac{\rho}{1-\rho}[\gamma + \Gamma] - \rho[\gamma + \Gamma], [\gamma + \Gamma] - (1-\rho)[\gamma + \Gamma]\right)$$

$$(\tau_t, \sigma_t) = (\tau, \sigma) = \left(\frac{\rho}{1-\rho}, 1\right)[\gamma + \Gamma], t > 0 \qquad (17)$$

The above expression is precisely equation (13), as expected. However, in general we expect changes in the cost coefficients γ_t and Γ_t and in the values of states benefits β_{st} as well. The changes in the cost parameters will call for constant adjustments in the tax-subsidy benefits because they are observable.

On the other hand, the changes in the benefits are not observed by the government and the consequence of this incomplete information is that the country's NDCs will not be met, in general. However, we expect that the errors will have a zero mean so that the emissions will oscillate around the NDCs. We call this constantly adjusted policy and its effect on emissions the "tatonnement policy".

4.2.3. The progressive adjustment policy

Expression (16) presents the optimal fiscally neutral tax policy that a country should use if it whishes to reach a volume of emissions close to its NDCs in one time period.

Any tax policy, however, is distorting and creates addition costs and burdens on the private agents. These distortions are higher, the higher are the tax rates. In addition, since the burden is decentralized to the subnational governments, a high powered tax policy may bring about strong political opposition.

This is the main rationale behind the international consensus that the NDCs should be reached in the medium term, in the 2030. Therefore, considering the 2030 deadline, a country may smooth the path towards its commitments, so that the burden to the country could gradually increasing.

Under this view, the optimal tax/subsidy policy can be redesigned in the following way. First, set the time period horizon η for (approximately) reaching the NDCs. For example, starting in 2023, $\eta = 7$ to reach the goal in 2030.

Then, the optimal progressive policy schedule is:

$$(\tau_t, \sigma_t) = \left(\frac{\frac{t}{\eta}\rho}{1 - \frac{t}{\eta}\rho} [\gamma_{t-1} + \Gamma_{t-1}] - \frac{t}{\eta}\rho[\gamma_t + \Gamma_t], [\gamma_{t-1} + \Gamma_{-1}] - \left(1 - \frac{t}{\eta}\rho\right)[\gamma_t + \Gamma_t] \right) \quad (18)$$

Under this policy, in the first period $t = 1$ the tax-subsidy will correspond to $\frac{100}{\eta}$ percentage of the optimal power of the policy.

In the second period, the power will doble, to $2\frac{100}{\eta}$ percentage of the optimal.

Finally, in period η the full power of the mechanism will be used.

Due to this progressive policy adjustment, the emissions reduction between two time periods will be much lower that under the previous section policy, allowing society to adapt more gradually to the new standards.

Such a policy has several advantages. First, it reduces the extra burden of this taxation from one period to the next. Second, it shows the commitment of the country to reach the NDCs in the expected period. Third, it allows time for new technological progress to be adopted in the production process, reducing the benefits of emissions and, thereby making it less costly to the private agents to adjust to the new environment.

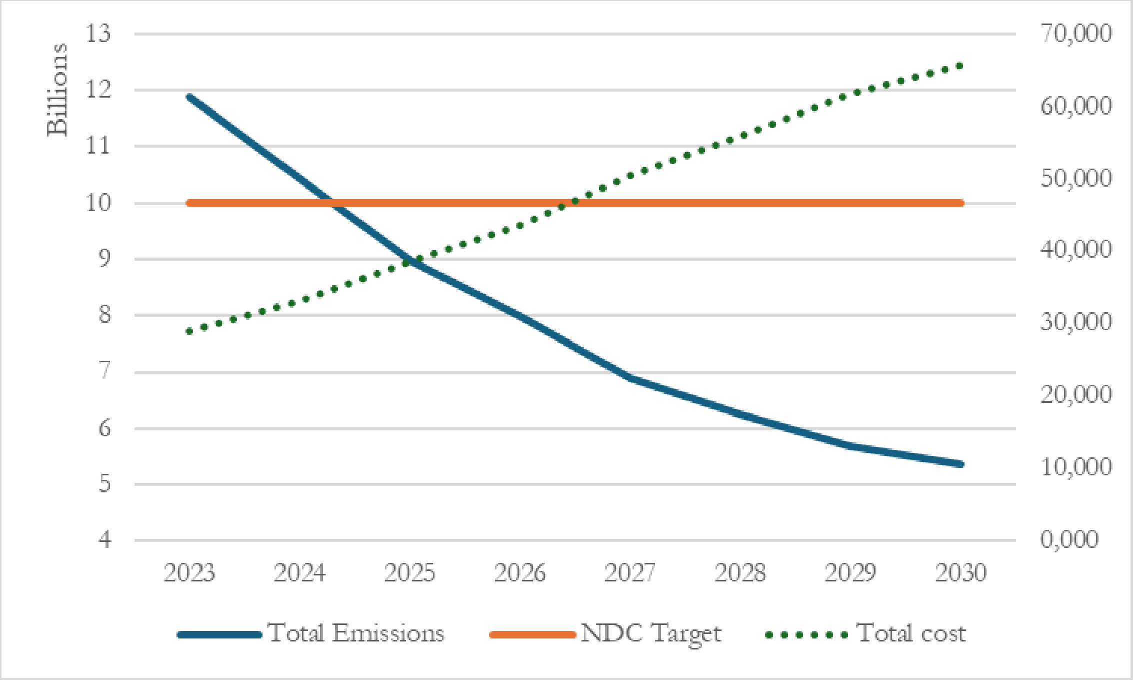
5. Initial Empirical Results

Using the results obtained in the Theoretical Framework (section 4), we explore the data on emissions in 2022 to examine the empirical results of the simulations. The results will be presented following the two sections: (i) complete information; and (ii) incomplete information. Notice that here, we assume complete information as the case when players knowing all aspects of the game structure, including payoffs, strategies, and the consequences of each action, but the subnational governments do not internalize social costs of carbon. Incomplete information is the case when there is a degree of variability in the expected benefit from emitting more.

5.1. Complete information

We began our empirical assessment under imperfect information regarding carbon price behavior, but with perfect information regarding the cost of other states and their emissions (including the social cost of carbon). Our results indicate that aggregated emissions will reach the 2030 NDC target by 2025 (Figure 1- Evolution of Emissions under Price Uncertainty when Agents Internalize Social Cost below).

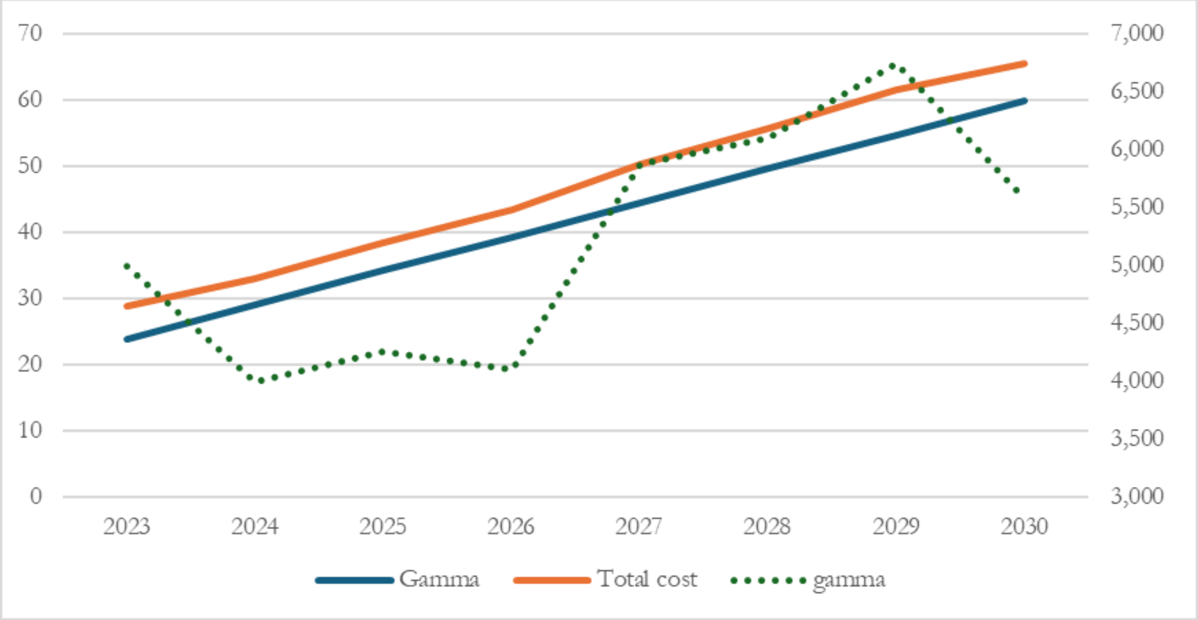
Figure 1- Evolution of Emissions under Price Uncertainty when Agents Internalize Social Cost



Source: author elaboration.

This result occurs mainly due to the evolution of the total cost of emission rising; I.e., increase in the opportunity cost of emitting and the social cost of carbon (γ, Γ respectively) - Figure *2* - Evolution of the Total Cost of Emission. However, literature suggests that the environment, as a common good, suffers from individual agents benefiting directly from exploiting resources while sharing the costs of depletion (Hardin, 1968; Diekert, 2012; Olstom, 1998). Therefore, it is reasonable to assume a bounded rationality scenario, where subnational entities do not incorporate overall emissions into their utility functions. In this case, Γ would be zero and only γ would factor into their decision making.

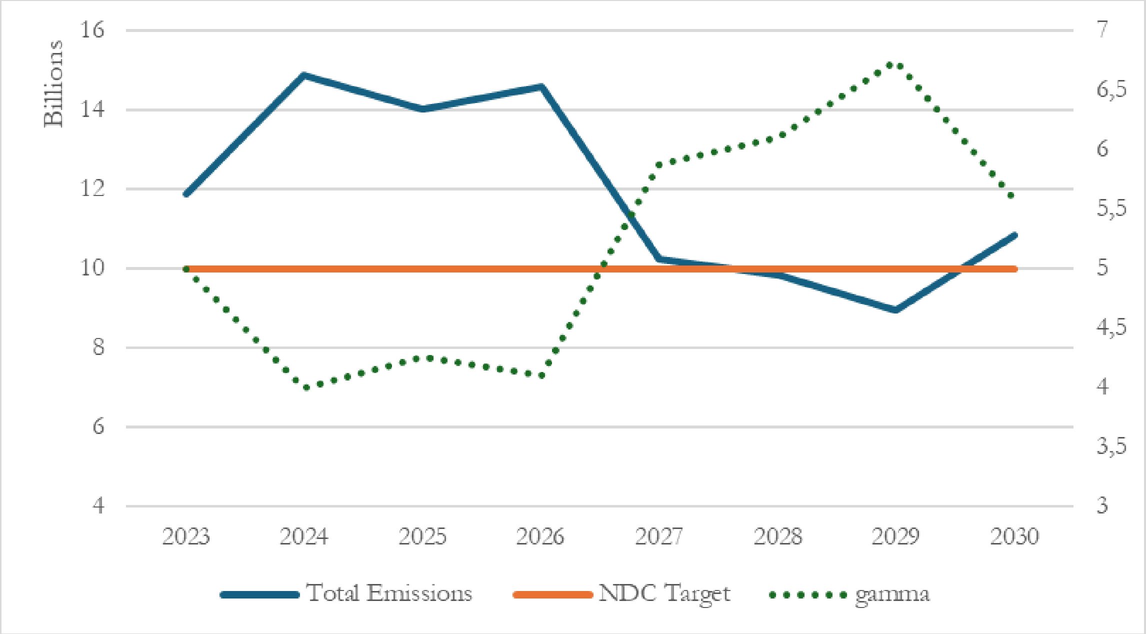
Figure 2 - Evolution of the Total Cost of Emission



Source: author elaboration.

Therefore, we proceed to analyzing the results of emissions when agents have bounded rationality, i.e., the social costs of carbon are not internalized into their decision-making – Figure *3* - Evolution of Emissions under Price Uncertainty when Agents with no Social Cost. Under this scenario, we could reach the NDC target, but this relies heavily on the price of carbon in the market. Therefore, a strict market mechanism will likely be insufficient to internalize social costs of carbon so that subnational entities will reach their NDC targets.

Figure 3 - Evolution of Emissions under Price Uncertainty when Agents with no Social Cost

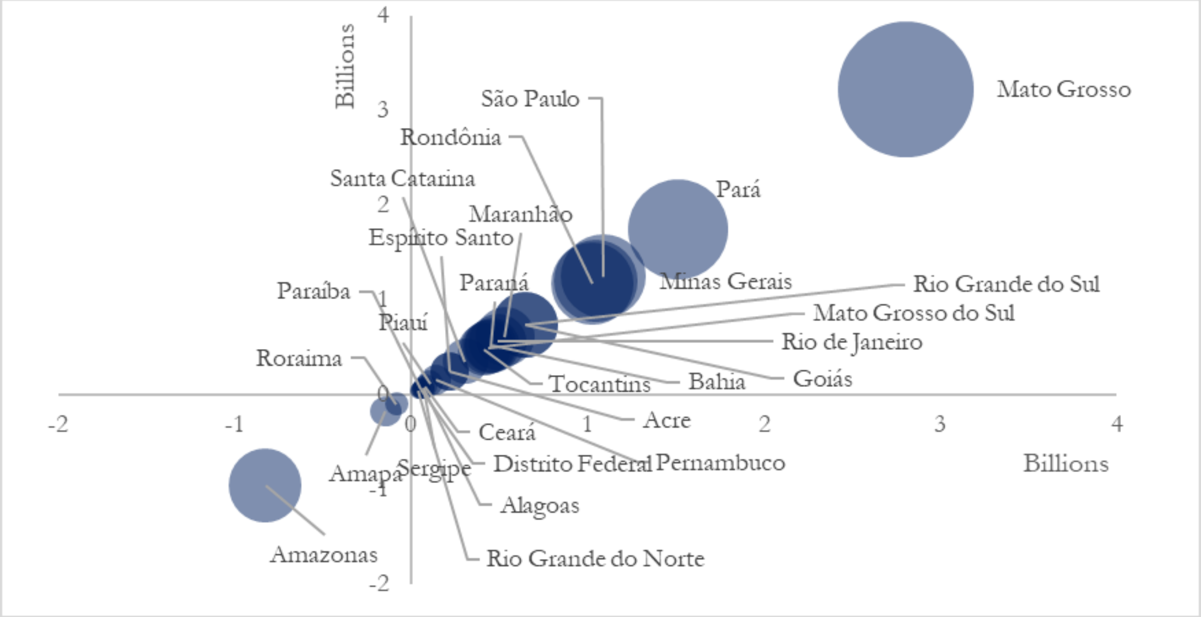


Source: author elaboration.

The assessment based on simulated emissions per state signals a positive relation for all states, i.e., all regions of Brazil would have incentives to increase emissions, not reduce them (Figure *4* - State Level Simulated Emissions when Social Cost is not Internalized below). Furthermore, states that are carbon negative (like Amazonas, Roraima and Amapá) increase their emissions. In particular, the size of the increase is similar between Amazonas, Pará, Rondônia, São Paulo, and Minas Gerais – three states in the legal amazon region (Amazonas, Pará and Rondônia would significantly increase emissions under a no mechanism rule with carbon price uncertainty).

The state can, therefore, proceed to imposing a fiscal policy (τ, σ) such that the states comply with state level targets (Figure *4* - State Level Simulated Emissions when Social Cost is not Internalized).

Figure 4 - State Level Simulated Emissions when Social Cost is not Internalized



Source: author elaboration.

In the case of complete information regarding state behavior and the risk regarding carbon price behavior, the central government can set τ, σ such that the states comply with state level targets so that the country will reach the NDC target at t=2 and onward (Table *3* - Emissions after Implementation of Mechanism, with complete information). Notice that as the carbon price shifts and once the level of emissions we have targeted is reached, we need a very small incentive to maintain the level of emissions aligned with the NDCs. This may indicate that a fiscal mechanism may be needed to assist in consolidating a market mechanism and achieve lower emission levels.

Table 3 - Emissions after Implementation of Mechanism, with complete information

Year	Total_Emissions	Tau (τ) + Sigma (σ)	gamma (γ)
2023	11.872.119.540	N/A	5
2024	10.004.176.615	2,169	3,995
2025	10.004.176.615	1,906	4,258
2026	10.004.176.615	2,063	4,1
2027	10.004.176.615	0,290	5,874
2028	10.004.176.615	0,056	6,108
2029	10.004.176.615	-0,581	6,745
2030	10.004.176.615	0,582	5,582

Source: author elaboration.

5.2. Incomplete information

Under the incomplete information case, we assume beta behaves as a random variable with expected value equal to B. Due to the incomplete information regarding β, the values of tau and sigma (τ, σ) vary significantly – Table *4* - Values of Tau and Sigma under Incomplete Information. This result may indicate a more critical role of fiscal instruments to induce compliance with target emission levels in the presence of risk. It is noteworthy that we assume that although the Central Government does not know the exact β, it knows the probability distribution function.

Table 4 - Values of Tau and Sigma under Incomplete Information

Year	Total_Emissions	Tau (τ) + Sigma (σ)
2023	11.872.119.540	N/A
2024	10.004.176.615	35,36445561
2025	10.004.176.615	3,815646437
2026	10.004.176.615	-4,057003135
2027	10.004.176.615	8,001334362
2028	10.004.176.615	0,150478646
2029	10.004.176.615	-4,146950328
2030	10.004.176.615	15,26897634

Source: author elaboration.

Under the tatonnement strategy, central government will adjust τ, σ such that the states comply with state level targets (*Table 5 - Tatonnement Approach* bellow), but in a recursive manner. Because the Central Government does not know the probability distribution function of the states or, equivalently, the cost of precisely identifying tau and sigma (τ, σ) is too high, then it can implement a fiscal strategy that changes according to state-level decision. We tested if changes in the rule of adaptation for tau and sigma would alter the results; they do not (please refer to annex for further detail).

Table 5 - Tatonnement Approach

Year	Total_Emissions	Tau (τ)	Sigma (σ)	Tau (τ) + Sigma (σ)
2023	13.771.658.666	10	10	20
2024	13.008.759.775	12	11	23

2025	11.630.439.010	14	12	26
2026	9.311.143.498	16	13	29
2027	10.504.821.370	14	12	26
2028	9.741.759.241	16	13	29
2029	10.166.448.584	14	12	26
2030	8.835.735.170	16	13	29
NDC Commitment	**10.004.176.615**			

Source: author elaboration.

6. Discussion on empirical results and next steps

Our results indicate that in a scenario with perfect information and full rationality, Brazil would likely meet its NDC emission targets. However, when we take into account bounded rationality, where agents do not internalize social cost of emissions, in the absence of clearly defined, target-driven fiscal instruments, Brazil is unlikely to consistently meet its 2030 Nationally Determined Contributions (NDCs). Also, under higher levels of risk, the need for harder fiscal policy is higher. Finally, under imperfect information with uncertainty, the incentive scheme can self-adapt based on individual state-level decision-making and lead to NDC emission target compliance.

In the absence of a specific mechanism and with uncertainty in carbon prices, our findings reveal that the three states with the highest projected emissions are in the Legal Amazon region. Although biodiversity loss was not considered a factor in setting tax and subsidy levels in our study, this is an important area for future research. The social cost of deforestation is notably higher in regions with greater biodiversity.

In the presence of a small level of fiscal intervention ($\tau = 10; \sigma = 10$), we find that the NDC is met and dynamically adjusted in a decentralized manner, as price of carbon in the market fluctuates. This suggests that fiscal policy can effectively serve as a buffer for market mechanisms to mature.

Moving forward, the study will incorporate the influence of inter-state dynamics in adopting mitigation strategies, and a municipal-level analysis. Aligned with the literature on fiscal diffusion, our simulations will investigate whether there is a propensity for states to emit less when neighboring states reduce their emissions and begin receiving substantial subsidies. Applying this model to municipalities will enable us to assess the likelihood of consortium formation among smaller municipalities to meet their targets and evaluate the incentive for collective local action.

Finally, we will conduct a sensitivity analysis by examining the changes in emissions as we alter the model calibration and perform a robustness check of our current model by comparing past emission predictions with realized emissions.

7. Conclusion

Despite the growing interest in sustainable and green practices (Smith, 2020; Johnson & Wang, 2021), Brazil still faces significant challenges in achieving its Nationally Determined Contributions (NDCs). Given the complexity of its federative system, where taxes and subsidies significantly impact economic and environmental outcomes (Oliveira, 2019; Souza & Pereira, 2022), this paper explores how a decentralized mechanism could induce compliance with NDC targets at the local level.

We consider price uncertainty and technological progress from 2023 to 2030. The targets are established proportionally to each sector's contribution to total emissions in the country. Under the assumption of perfect information on state behavior, we find that a decentralized mechanism can be effective in inducing compliance with NDC targets. Furthremore, even under incomplete information and uncertainty our study indicates compliance with NDC target emission levels. This suggests that a decentralized fiscal policy may work as a coordination mechanism to achieve overall levels of reductions.

However, our current model does not account for the effects of biodiversity loss or the influence of neighboring states on emission decisions. Future research will incorporate these aspects alongside sensitivity and robustness checks. The sensitivity analysis will involve altering parameters and analyzing outcomes, while the robustness check will compare outcomes over the past years to verify model alignment with historical results.

Additionally, further research should include an extension of our analysis to municipal-level behavior to examine how municipalities behave and whether they have incentives to form consortiums for environmental protection and emission reduction.

This study is novel in that it presents a budget-neutral form of federative coordination for NDC compliance, considering state-specific factors. Our work aligns with the literature on fiscal federalism and fiscal policy diffusion, while addressing the common goods and externalities issues inherent in environmental policy (e.g., Tiebout, 1956; Oates, 1999).

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9. Appendices

List of Brazilian States, with abbreviation and region.

State	**Abbreviation**	**Region**
Acre	AC	North
Alagoas	AL	Northeast
Amapá	AP	North
Amazonas	AM	North
Bahia	BA	Northeast
Ceará	CE	Northeast
Distrito Federal	DF	Central-West
Espírito Santo	ES	Southeast
Goiás	GO	Central-West
Maranhão	MA	Northeast
Mato Grosso	MT	Central-West
Mato Grosso do Sul	MS	Central-West
Minas Gerais	MG	Southeast
Pará	PA	North
Paraíba	PB	Northeast
Paraná	PR	South
Pernambuco	PE	Northeast
Piauí	PI	Northeast
Rio de Janeiro	RJ	Southeast
Rio Grande do Norte	RN	Northeast
Rio Grande do Sul	RS	South
Rondônia	RO	North
Roraima	RR	North

Santa Catarina	SC	South
São Paulo	SP	Southeast
Sergipe	SE	Northeast
Tocantins	TO	North

Differences Between Tau and Sigma rule of change

Tau changes in units of 2, while sigma in unit of 1.

Year	Total_Emissions	Tau (τ)	Sigma (σ)	Tau (τ) + Sigma (σ)
2023	13.771.658.666	10	10	20
2024	13.008.759.775	12	11	23
2025	11.630.439.010	14	12	26
2026	9.311.143.498	16	13	29
2027	10.504.821.370	14	12	26
2028	9.741.759.241	16	13	29
2029	10.166.448.584	14	12	26
2030	8.835.735.170	16	13	29
NDC Commitment	**10.004.176.615**			

Source: author elaboration.

Tau and sigma change in 2 units each.

Year	Total_Emissions	Tau	Sigma
2023	13.771.658.666	10	10
2024	12.542.145.583	12	12
2025	10.890.087.478	14	14
2026	8.586.279.721	16	16
2027	9.898.956.799	14	14
2028	11.316.276.452	12	12
2029	9.636.474.495	14	14
2030	10.087.693.208	12	12
NDC Commitment	**10.004.176.615**		

Source: author elaboration.

Tau changes in unit of 1, while sigma in units of 2.

Year	Total_Emissions	Tau	Sigma
2023	13.771.658.666	10	10
2024	13.008.759.775	11	12
2025	11.630.439.010	12	14
2026	9.311.143.498	13	16

2027	10.504.821.370	12	14
2028	9.741.759.241	13	16
2029	10.166.448.584	12	14
2030	8.835.735.170	13	16
NDC Commitment	**10.004.176.615**		

Source: author elaboration.