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Convergence and Determinants of Carbon Emissions in Brazilian Agriculture

Convergência e Determinantes das Emissões de Carbono na Agricultura Brasileira

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Abstract

This paper presents empirical evidence of the convergence of carbon dioxide (CO^2) emissions from managed agricultural soils (direct emissions from agriculture) and their determinants for the Brazilian states during the period from 1975 to 2019. For this purpose, the log t-test and a clustering algorithm are used to investigate the characteristics of the convergence process of CO^2 emissions in agriculture. Subsequently, a Probit model is used to identify the factors that determine the formation of convergence clubs. Employing this econometric approach, we identify two convergence clubs. One club consists of 9 (33%) Brazilian states with high CO^2 emissions in agriculture, while the other is formed of 18 (67%) states with low emissions. Land use, labor, capital, bovine density, agricultural production, industrial production, rural credit, and energy consumption are identified as drivers for the formation of these convergence clubs. Finally, when comparing the CO^2 emissions of these clubs before and after the implementation of the Kyoto Protocol, we find that environmental sustainability has been widely neglected in Brazilian agriculture.

Keywords: convergence analysis; carbon dioxide emissions; agriculture; managed soils; Brazil.

JEL Code: Q1; Q52; Q53.

Resumo

Este artigo apresenta evidências empíricas da convergência das emissões de dióxido de carbono (CO^2) de solos agrícolas manejados (emissões diretas da agricultura) e seus determinantes para os estados brasileiros durante o período de 1975 a 2019. Para isso, o teste log t e um algoritmo de agrupamento são usados para investigar as características do processo de convergência das emissões de CO^2 na agricultura. Posteriormente, um modelo Probit é usado para identificar os fatores que determinam a formação de clubes de convergência. Empregando essa abordagem econométrica, identificamos dois clubes de convergência. Um clube é formado por 9 (33%) estados brasileiros com altas emissões de CO^2 na agricultura, enquanto o outro é formado por 18 (67%) estados com baixas emissões. O uso da terra, a mão de obra, o capital, a densidade de bovinos, a produção agrícola, a produção industrial, o crédito rural e o consumo de energia são identificados como fatores determinantes para a formação desses clubes de convergência. Por fim, ao compararmos as emissões de CO^2 desses clubes antes e depois da implementação do Protocolo de Kyoto, constatamos que a sustentabilidade ambiental tem sido amplamente negligenciada na agricultura brasileira.

Palavras-chave: análise de convergência; emissões de dióxido de carbono; agricultura; solos manejados; Brasil.

Códigos JEL: Q1; Q52; Q53.

1. INTRODUCTION

Global warming is one of the most pressing environmental issues the world faces today. Greenhouse gas emissions (GHGs), largely stemming from economic globalization processes, are now more than ever recognized as a driving force behind climate change (Adebayo et al., 2021; Li et al., 2020). This recognition has led both developed and emerging countries to commit to reducing GHG emissions and to develop policies to address climate challenges at the international level (Panopoulou and Pantelidis, 2009). In recent times, countries have taken various commitments to reduce environmental degradation, mainly through medium and long-term carbon emission reduction targets. One of the initiatives that highlights these efforts is the Kyoto Protocol (1997), which came into effect in 2005 (Payne, 2020). Although countries are more concerned about environmental issues in this century, carbon dioxide (CO^2) emissions, one of the main causes of global warming, already exceed 41 billion tons emitted annually (Ivanovski and Churchill, 2020).

Among economic sectors, it is estimated that agriculture is responsible for approximately 10% of global CO^2 emissions. In recent decades, agricultural emissions have been growing at an average rate of 0.5% per year worldwide.[1] These carbon emissions are expected to continue growing in the coming decades, as this sector is one of the drivers of economic growth and exports in developing countries (Martinelli et al., 2010). These substantial levels of carbon emissions associated with agriculture have spurred a growing body of literature dedicated to exploring the environmental impacts of the development of this economic activity (see, for example, Raihan et al. (2022), Ridzuan et al. (2020), Prastiyo et al. (2020), Balsalobre-Lorente et al. (2019), and Appiah et al. (2018)). Previously, other studies have focused on analyzing the impact of economic growth (Khan et al. (2020), Ito (2017), and Aye and Edoja (2017)), energy consumption (Khan et al. (2019), Paramati et al. (2017), and Kais and Sami (2016)), trade (Mahmood et al. (2019) and Meng et al. (2018)), financial development (Khan and Ozturk (2021) and Salahuddin et al. (2018)), research and development (Churchill et al. (2019) and Fernández et al. (2018)), among other factors that may influence carbon emissions (see Shahbaz and Sinha (2019) for a comprehensive review).

In the wake of the literature examining the determinants of environmental degradation, investigations focusing on the spatial distribution of GHG emissions have emerged (Ivanovski and Churchill, 2020). Supported by the theoretical framework developed by Brock and Taylor (2010), which incorporates pollution flows into Solow's (1956; 1957) economic growth model to provide a reasonable economic explanation for the Environmental Kuznets Curve (EKC) (Grossman and Krueger, 1995), a branch of this area of research is increasingly examining environmental convergence (Pettersson et al., 2014). The main direction of this branch has been convergence in GHG emissions levels, with CO^2 emissions being the most analyzed (Payne, 2020). In particular, the non-stationary properties of these emissions with respect to a common trajectory are examined (Lee et al. (2023), Zhu and Lin (2020), Ivanovski and Churchill (2020), Yu et al. (2018), Runar et al. (2017), Apergis and Payne (2017), Wu et al. (2016), Burnett (2016), Zhao et al. (2015), and Panopoulou and Pantelidis (2009)). These studies are recognized for playing an important role in the deliberate learning of comprehensive and targeted strategies to reduce greenhouse gas emissions in different sectors and spatial scales (Ivanovski and Churchill, 2020).

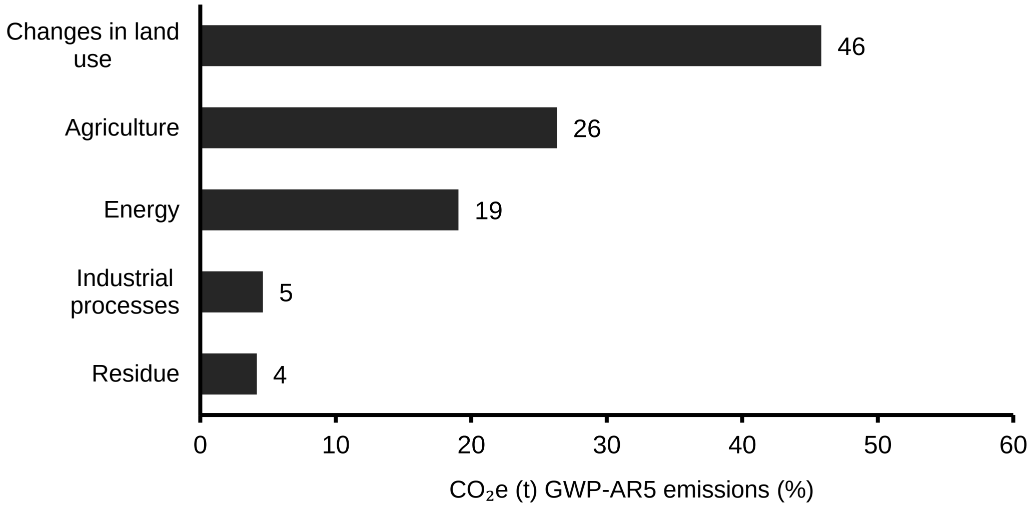
To contribute to these two fields of environmental economic literature, we base our analysis on the economic model proposed by Brock and Taylor (2010), which allows for the prediction of emissions convergence among economies at different stages of development. This prediction is substantiated by the EKC hypothesis, which posits an inverted U-shaped relationship between environmental pollution and economic development (Sarkodie and Strezov, 2019). Environmental convergence (i.e., convergence in emissions) can be understood as a phenomenon in which economies with higher carbon emissions tend to converge toward lower emission levels as they reach higher levels of development (Lawson et al., 2020). As highlighted by Ivanovski and Churchill (2020) and

[1] Information obtained from Our World in Data (September 24, 2023).

Ivanovski et al. (2018), there are still few studies that use disaggregated longitudinal data on carbon emissions and address the heterogeneity of states within countries, i.e., that control the economic characteristics of regions, such as capital, technology, infrastructure, economic resources, and institutional quality.

Considering this context, this paper presents empirical evidence on the convergence of carbon dioxide (CO^2) emissions in the agricultural sector related to soil management (direct emissions from agriculture) and its determinants for the states of Brazil during the period from 1975 to 2019. Brazil offers an attractive scenario for at least two reasons. First, Brazilian agricultural production totaled US$ 88.2 billion in 2019, making the country one of the top five food producers in the world.[2] Second, the country is among the nations that contribute the most to global warming (Adebayo et al., 2021). Annually, the Brazilian economy emits more than 2,148 million tons of CO^2 equivalent (CO^2e) with global warming potential (GWP-AR5). Of these emissions, approximately 26% are attributed to agricultural activities (see Fig. 1). Of the total of 565 million tons of CO^2e generated by this sector, about 30% are due to soil management. Therefore, we conducted an environmental convergence analysis in a highly relevant context for the formulation of CO^2 emissions mitigation policies.

Fig. 1 Distribution of CO^2e emissions by sector in Brazil, 2019



Source: Prepared by the authors, with data from the SEEG.

To investigate the convergence process in direct CO^2 emissions from agriculture (managed soils) in Brazilian states, we used a log t-test and the Phillips and Sul (2007) clustering algorithm. [3] Next, we estimated the factors determining the formation of convergence clubs in carbon emissions from agriculture through a Probit model. Employing this approach, we found evidence for the existence of two convergence clubs in CO^2 emissions from Brazilian agriculture associated with soil management. A convergence club is composed of 9 (33%) Brazilian states with high CO^2 emissions, and the other is formed of 18 (67%) states with low emissions. Land use, labor, capital, bovine density, agricultural production, industrial production, rural credit, and energy consumption are identified as drivers for the formation of these convergence clubs. Comparing the CO^2 emissions of these convergence clubs before and after the Kyoto Protocol came into effect, we discovered that environmental sustainability in the Brazilian agricultural sector has been largely neglected.

The results obtained in this study contribute to an evolving literature that examines the process of convergence in carbon emissions and its determinants in the agricultural sector in various ways (Akran and Ali (2021), Akram et al. (2020), Wu et al. (2019), Morales-Lage et al. (2019), and Oliveira and Bourscheidt (2017)). Firstly, we examined the CO^2 emissions from managed soils in Brazil, also referred to as direct emissions from the agricultural sector, for the first time. These

[2] Information obtained from IBGE (September 24, 2023).
[3] The main advantage of this approach is that it captures the heterogeneity of economies without imposing specific assumptions of stochastic stationarity on the trend (Apergis and Payne, 2017).

emissions result from the intensive use of limestone and urea (fertilizers), which are widely utilized inputs in national agriculture to control soil acidity and increase land productivity for cultivation (Zilli et al., 2020; Melo Benites et al., 2023). Second, most studies conducted on carbon emissions in agriculture focus on the national level, masking subnational differences or suffering from data imprecision in carbon emissions since countries adopt different methods to calculate their pollution levels. By concentrating our analysis on the convergence process of agricultural emissions at the state level within a single country, we minimize the potential bias associated with data heterogeneity across countries (Ivanovski and Churchill, 2020). Third, in studying this form of pollution, we employ a temporal horizon that enables us to capture changes in Brazilian agricultural production and the dynamics of its carbon emissions (1975-2019). This sets us apart from other studies conducted for Brazil, which rely on carbon emissions data only from the 1990s onwards (see, for example, Amorim et al. (2023) and Amarante et al. (2022)). Finally, we add new evidence on the factors influencing the accumulation of CO^2 emissions in agriculture, specifically for managed soils.

The remainder of the study is organized as follows. The next section provides a theoretical review of economic and environmental convergence and convergence clubs. Then, in Section 3, we discuss the details of the empirical data and the methodology of Phillips and Sul (2007). Section 4 presents the results. Finally, Section 5 presents the conclusions and policy recommendations for Brazil.

2. THEORETICAL REVIEW

2.1 Economic convergence and convergence clubs

Economic convergence has played a key role in economic growth theory since the seminal study by Baumol (1986). This seminal study hypothesized that poorer economies are able to catch up with more advanced economies in terms of per capita income over time. Based on Solow's (1956; 1957) growth model, Barro and Sala-i-Martin (1992) and Mankiw et al. (1992) provide concrete evidence of this phenomenon. These early studies showed that when preferences and technologies are similar across countries, differences in per capita income between lagging and advanced economies tend to gradually decrease, leading to convergence to a common steady state (Sofi and Durai, 2016; Borsi and Metiu, 2015). In other terms, they confirm the prediction of the Solow model, which, based on the assumption of diminishing returns of the capital stock to output, anticipates convergence of incomes across economies in the long run.

Durlauf and Johnson (1995) and Hansen (2000) showed that, instead of a single global equilibrium, convergence could occur within different economic groups, each with distinct balanced growth regimes. This implies that multiple locally stable equilibria can emerge as a result of a dynamic system, which tends to lead to different growth patterns (Ergodan and Okumus, 2021). These distinct growth patterns are referred to as “convergence clubs”, a term coined based on the contributions of Quah (1996). Following this discussion, Galor (1996) emphasizes that the analysis of economic convergence has been centered on three hypotheses:

a) *Unconditional convergence:* Over time, all economies reach the same per capita income level, regardless of their starting conditions.

b) *Conditional convergence:* Economies with similar structural factors like investment rates, technology, human capital, population growth, and policies will converge in the long term, irrespective of their initial conditions.

c) *Convergence clubs:* Economies with both similar structural characteristics and identical initial conditions will form clubs and converge to the same per capita income level in the long run.

2.2 Environmental convergence

This paper is based on this theoretical framework, as well as on the early studies of economic convergence that were guided by the Solow model. We follow a perspective that fits into the concept of environmental convergence clubs. This approach is supported by the contribution of Brock and Taylor (2010), who introduced essential considerations about pollutant emission flows, notably carbon emissions, within the framework of the Solow growth model. This theoretical model, known as the “Green Solow”, lays the necessary groundwork for conducting empirical studies on the process of convergence or divergence of economies with respect to carbon emissions. In the case of this study, we focus on carbon emissions (CO^2) from agricultural production.

Environmental convergence corresponds to a phenomenon in which environmental disparities (carbon emissions) between different economies tend to decrease as these economies develop economically and adopt more sustainable policies and practices (Lawson et al., 2020; Bulte et al., 2007). This concept of environmental convergence is based on two fundamental economic premises. First, it is linked to the convergence assumptions outlined by Galor (1996). Second, it is grounded in the theory of the Environmental Kuznets Curve (EKC), originally proposed by Grossman and Krueger (1995). According to the EKC hypothesis, environmental pollution tends to increase in parallel with economic growth in the early stages of development but tends to decrease as income reaches higher levels from a long-term perspective of economic development.

The Green Solow model developed by Brock and Taylor (2010) offers a coherent explanation that links economic and environmental convergence.[4] Specifically, this model shows that the validity of the EKC is an intrinsic outcome of the convergence process toward a sustainable growth pattern. To achieve this, the model assumes that environmental pollution is an inherent byproduct of consumption in capitalist society. In this context, technological changes in the productive sector become inevitable to promote the expansion of wealth. Consequently, technological progress to reduce environmental degradation must outpace the pace of average production growth. In practice, this reduction in pollution becomes tangible through initiatives that lead to increasing returns to scale. These gains are generally achieved through investments in clean and efficient technologies that promote the rational use of factors of production (Pettersson et al., 2014).

Brock and Taylor (2010) argue that exogenous technological transformations play a central role in determining the long-term growth of economies. This premise supports the idea that carbon emissions tend to decrease as income rises to higher levels. This leads to a conditional convergence of carbon emissions toward the steady state. In the short term, however, each economy converges on its own growth path, both in terms of income and carbon emissions. From this perspective, it is possible to observe a scenario in which economies with modest growth rates face an increase in carbon emissions, while those with more pronounced growth rates may experience a decrease in pollution. In this regard, differences in income growth rates across economies prove to be an important factor. If these differences are significant, there is a possibility that carbon emissions will diverge across economies. Conversely, if these differences are reduced, space opens up for convergence among economies in terms of carbon emissions (Pettersson et al., 2014).

This theoretical review provides the economic foundation for analyzing carbon emissions (CO^2) resulting from the growth of production and income in the agricultural sector of Brazil. The only explicit difference is that we are considering only income derived from agricultural activity, that is, the idea of economic growth in agriculture. Furthermore, the concepts of environmental convergence (i.e., the convergence of carbon emissions) and environmental convergence clubs (i.e., carbon emissions clubs) are analogous to the concepts of economic convergence and convergence clubs presented in section 2.1.

3. METHODOLOGY

3.1 Data

This study uses a balanced panel data set from all 27 federal units of Brazil – 26 states and the Federal District – and covers the period from 1975 to 2019.[5] CO^2 emissions from the agricultural sector are from the *Sistema de Estimativas de Emissão de Gases de Efeito Estufa* (SEEG – Brazil).[6]

[4] The derivation of the Green Solow model can be found in Brock and Taylor (2010).

[5] The Federal Units (FU) of Brazil are: Acre (AC), Alagoas (AL), Amapá (AP), Amazonas (AM), Bahia (BA), Ceará (CE), Distrito Federal (DF), Espírito Santo (ES), Goiás (GO), Maranhão (MA), Mato Grosso (MT), Mato Grosso do Sul (MS), Minas Gerais (MG), Pará (PA), Paraíba (PB), Paraná (PR), Pernambuco (PE), Piauí (PI), Rio de Janeiro (RJ), Rio Grande do Norte (RN), Rio Grande do Sul (RS), Rondônia (RO), Roraima (RR), Santa Catarina (SC), São Paulo (SP), Sergipe (SE), and Tocantins (TO).

[6] The methodology for estimating greenhouse gasses (GHGs), including CO^2 emissions from managed soil, can be found in the SEEG at the following address: www.seeg.eco.br. The State of Tocantins was established in 1988. Considering this, we applied a retrospective estimation method (retropolation method) of CO^2 emissions from agriculture for the emissions of this state from the year of its creation to 1975

CO^2 emissions from agricultural activity result from managed soils. [7] These CO^2 emissions are estimated based on the use of limestone and the application of urea, both of which are widely used in soil liming and agricultural fertilization. This form of pollution is called direct CO^2 emissions from agriculture (Kalkhoran et al., 2019).

To identify the factors that influence the formation of convergence clubs in CO^2 emissions from agriculture, we used information from different sources, such as the *Instituto de Pesquisa Econômica Aplicada* (IPEA), the *Instituto Brasileiro de Geografia e Estatística* (IBGE), and the *Banco Central do Brasil* (BACEN). We selected a set of variables associated with both the economic structure of Brazilian states, such as energy consumption and industrial production, and the production and inputs of the agricultural sector, including capital, labor, land use, and access to rural credit. In addition, we included bovine density as a measure of livestock activity. These variables were selected based on previous research showing their importance as drivers of CO^2 emissions in the agricultural sector (Liu et al., 2021; Xu and Lin, 2017). Therefore, they are also expected to influence the formation of convergence clubs in this study. A detailed description of the variables used can be found in Table A1 of the Appendix.

3.2. The log t-test and the convergence clubs

The log t-test developed by Phillips and Sul (2007; 2009) allows the analysis of the transitional behavior of carbon emissions from agriculture in Brazilian states during the period from 1975 to 2019.[8] The CO^2 emissions from agriculture in the Brazilian states are denoted by X_{it} , which can be decomposed into systematic h_{it} and transient g_{it} elements based on the time-varying nonlinear factor model, as shown in Eq. (1) (Zhu and Lin, 2020).

$$X_{it} = h_{it} + g_{it} \quad (1)$$

Eq. (1) is then transformed into Eq. (2) to separate these components and capture the stochastic trend:

$$X_{it} = \left(\frac{h_{it}+g_{it}}{u_t}\right) u_t = \vartheta_{it} u_t, \quad \text{for all } i \text{ and } t. \qquad (2)$$

where $u_t$represents the single shared component that captures the behavior of the deterministic or stochastic trend, while ϑ_{it} is a time-varying idiosyncratic element that captures the distance between X_{it} and u_t.

The convergence of carbon emissions (X_{it}) requires that the limit as t approaches infinity of $\lim_{t\to\infty} \frac{X_{it}}{X_{jt}} = 1$ is 1 for any i and j, which represents the convergence of the idiosyncratic element over time, where $\lim_{t\to\infty} \vartheta_{it} = \vartheta$ for any i. Now we assume an idiosyncratic element ϑ_{it} with the following equation:

$$\vartheta_{it} = \vartheta_i + \gamma_{it}\xi_{it}, \; with \quad \gamma_{it} = \frac{\gamma_i}{L(t)t^{\alpha}}, \; t \geq 1, \; \gamma_i > 0 \text{ for all } i. \quad (3)$$

where $L(t)$ is a slowly varying function, which can also be defined as $\log(t)$ or as a $\log[\log(t)]$. Monte Carlo simulations presented by Phillips and Sul (2007) suggest that $L(t) = \log(t)$ exhibits less size distortion and better statistical test power. The $\log(t)$ regression test by Phillips and Sul (2007) has the null hypothesis ($h_0: \vartheta_i = \vartheta$ when $\alpha \geq 0$), indicating the convergence of carbon emissions in the agricultural sector to the Brazilian states. Against the alternative hypothesis ($h_1: \vartheta_i \neq \vartheta$ when $\alpha < 0$), indicating the absence of convergence.

As u_t is a common factor in Eq. (2), it may be removed by scaling to give the relative load or transition coefficient (f_{it}). This relative transition parameter (f_{it}) is used to remove the common factor and isolate the trend factor, which depicts a temporal transition path of state economies (i), but now with respect to the panel average over time (t), as shown in Eq. (4). The Eq. (4) also indicates that the cross-sectional average is one unit, while its cross-sectional adjustment variance must

[7] Fig. C1 in the Appendix presents the evolution of CO^2 emissions from Brazilian agriculture. CO^2 emissions from this economic activity have been growing at an average rate of 6.2% per year in Brazil

[8] Prior to applying this methodological process, the longitudinal carbon emission data were filtered to eliminate the cyclic component using the Hodrick-Prescott (HP) smoothing filter. This filtering process allows us to capture the temporal trend of carbon emissions and then apply the Phillips and Sul (2007;2009) approach.

satisfy the conditions outlined in Eq. (5), that is, meet the convergence condition as time approaches infinity ($t \to \infty$) (Phillips and Sul, 2007).

$$f_{it} = \frac{X_{it}}{\frac{1}{N}\sum_{i=1}^{N} X_{it}} = \frac{\vartheta_{it}}{\frac{1}{N}\sum_{i=1}^{N} \vartheta_{it}} \quad (4)$$

$$F_{it} = \frac{1}{N}\sum_{i=1}^{N}(f_{it} - 1)^2 \to 0 \text{ if } \lim_{t\to\infty} \vartheta_{it} = \vartheta, \text{ for all } i. \quad (5)$$

The $\log(t)$ regression model proposed by Phillips and Sul (2007) is used to implement the hypothesis tests presented earlier:

$$\log\left(\frac{F_1}{F_t}\right) - 2\log\{\log(t)\} = a + b.\log(t) + \varepsilon_t, \text{ for } t = [rT], [rT] + 1, \cdots, T \text{ with } r > 0. \quad (6)$$

where $r \in (0,1)$ represents the initial proportion of the discarded sample. Phillips and Sul (2007) initially suggest using an $r \in \{0.2, 0.3\}$.

For $b = 2\alpha$, a robust one-sided t-test for heteroscedasticity and autocorrelation (HAC) can be used to test the inequality of the null hypothesis: $\alpha \geq 0$. Under certain technical assumptions, the asymptotic distribution of the log (t) regression statistic is $t_b = \frac{\hat{b}-b}{s_b} \Rightarrow N(0,1)$. In this context, the null hypothesis of convergence should be rejected at the 5% significance level if $t_b < -1,65$.

Although it is possible to reject the null hypothesis that would suggest a lack of convergence in CO^2 emissions from agriculture across the entire sample of states, it is important to consider the possibility of convergence within subgroups (clubs). Phillips and Sul (2007; 2009) provide a clustering algorithm, adjusted by Schnurbus et al. (2017), to identify clubs of convergence. We use this algorithm to identify convergence clubs in CO^2 emissions as well as the possibility of mergers between clubs. The result of this process is called final clubs. A detailed description of the process can be found in Du (2017).

3.3 The Ordered Probit model

In the second stage of the analysis, we are interested in identifying the factors that influence the formation of convergence clubs in CO^2 emissions in the agricultural sector. Specifically, we assume that the 27 Brazilian states can form J final convergence clubs, where we assign $Y_i \in \{1, 2, \ldots, J\}$ to to these clubs ordered by the average level of CO^2 emissions of each club, i.e., from the club with the lowest emissions to the highest, as in Eq. (7) (Zhu and Lin, 2020).

$$Y_i^* = X_i'\beta + \varepsilon_i\,, \quad i = 1, 2, \ldots, N \quad \text{and} \quad Y_i = \begin{cases} 1, & \text{if } Y_i^* \leq k_1 \\ 2, & \text{if } k_1 < Y_i^* \\ \vdots & \vdots \\ J, & \text{if } k_{J-1} < Y_i^* \leq k_j \end{cases} \quad (7)$$

Where X_i is a set of potential determinants for the formation of convergence clubs; β corresponds to the coefficient to be estimated; Y_i^* is the latent variable, representing convergence clubs for different cutoff points (k), while ε_i is a random error term, assumed to follow a normal distribution.

This empirical equation is estimated using the ordered Probit model, which involves estimating a conditional probability function with the categorical and ordered dependent variable. The coefficients to be estimated maximize the likelihood function of the model. However, when there are only two convergence clubs, a conventional Probit model is estimated, which has a similar econometric structure (Cameron and Trivedi, 2005).

4. RESULTS

4.1 Result of the log t-test and convergence clubs

This section presents the results obtained by the convergence modeling of Phillips and Sul (2007;2009) for CO^2 emissions in the agricultural sector of Brazilian states. Table 1 presents the results of the log t-test for CO² emissions in agriculture in all states for the period from 1975 to 2019. The test performed rejects the null hypothesis of convergence of emissions in all states at a 5% significance level with the estimate ($\hat{b} = -0.320$) and the statistic ($t_{\hat{b}} = -4.700$). This result indicates that the time series of CO² emissions in agriculture do not converge to a common steady state.

Table 1. Convergence clubs: CO² emissions from the agricultural

		N	$\hat{b}$ coeff.	Std.err	$t_{\hat{b}}$	$\hat{\alpha}$
Panel A. Club convergence tests						
All states		27	-0.320	0.068	-4.700*	
Club 1	MT, MG, SP, PR, RS, GO, MS, TO, PA.	9	0.174	0.066	2.658	0.087
Club 2	BA, SC, PI, MA, CE, ES, RO, SE, AL, PB, PE, RN, DF, AM, RJ, AC, RR, AP.	18	0.141	0.109	1.287	0.071
Panel B. Merging analysis						
No clubs can be merged.						
Panel C. Final club convergence						
Club 1	MT, MG, SP, PR, RS, GO, MS, TO, PA.					
Club 2	BA, SC, PI, MA, CE, ES, RO, SE, AL, PB, PE, RN, DF, AM, RJ, AC, RR, AP.					

Source: Prepared by the authors.

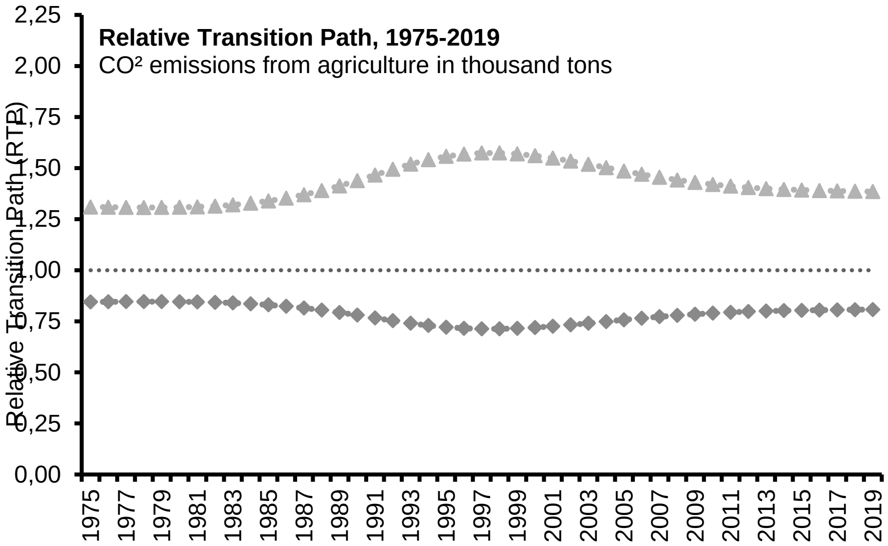
Notes: Table reports the log(t) regression test. $\hat{\alpha}$ is the speed of adjustment parameter calculated as $\hat{b}\backslash 2$. (*) Indicates rejection of the null hypothesis of convergence at the 5% level.

The absence of absolute convergence for all Brazilian states leads to the regression of log (t) for a second level of analysis, where the null hypothesis of the existence of convergence clubs is tested. Following the approach of Phillips and Sul (2007; 2009), we identify two convergence clubs in CO² emissions in the agricultural sector, since we cannot reject the null hypothesis at the 95% confidence level. Using this procedure, we identify a club with high CO² emissions in agriculture, composed of 9 (33%) Brazilian states, and another club with low emissions, formed of another 18 (67%) states. Since $b = 2\alpha$, the rate of convergence of the clubs can be calculated as $\alpha = b/2$, with $0 \leq \alpha < 1$. Thus, the convergence clubs of high and low CO² emissions in agriculture conditionally converge (convergence of growth rates) at a rate of 0.087 and 0.071, respectively. Although the value of $\hat{\alpha}$ for CO² emissions suggests a relatively low rate of adjustment, the convergence of growth rates is still achieved for the identified clubs. We examine this form of convergence in more detail in Section 4.3, where we use a model that controls for unobservable and time-invariant factors affecting CO² emissions in Brazilian agriculture.

The spatial distribution of Brazilian states in clubs of high and low CO² emissions in agriculture, as well as the average CO² emissions in thousand tons from 1975 to 2019, are presented in Figs. B1 and B2 in the Appendix. The states that make up the high CO² emissions in agriculture club are located in the Central-West, South-East, and South Brazil regions, where competitive agriculture is developed with intensive use of technology and modern inputs for soil management and achieving economies of scale in food production. On the other hand, the states that make up the club of low CO² emissions are located in the North and Northeast of the country, where agricultural activity is still developing traditionally, i.e., with low technological intensity and severe limitation of economic resources (Pereira et al., 2012).

The relative transition paths (RTPs) for the two convergence clubs, corresponding to the steady-state trajectory of the clubs approximated by the mean of the filtered CO² emission series, are presented in Fig. 2. As can be seen, Club 1 (high emission) remains above the stability line, while Club 2 (low emission) remains below it. The trajectory indicates that agricultural production in the Brazilian states still faces significant challenges in reducing carbon emissions and improving environmental sustainability in the clubs. This requires urgent changes in the production system, especially in the context of global warming and the paradigm shift that is taking place in the agricultural sector (Amorim et al., 2023; Martinelli et al., 2016).

Fig. 2 Average transition paths per club – CO^2 emissions from agriculture



Source: Prepared by the authors.

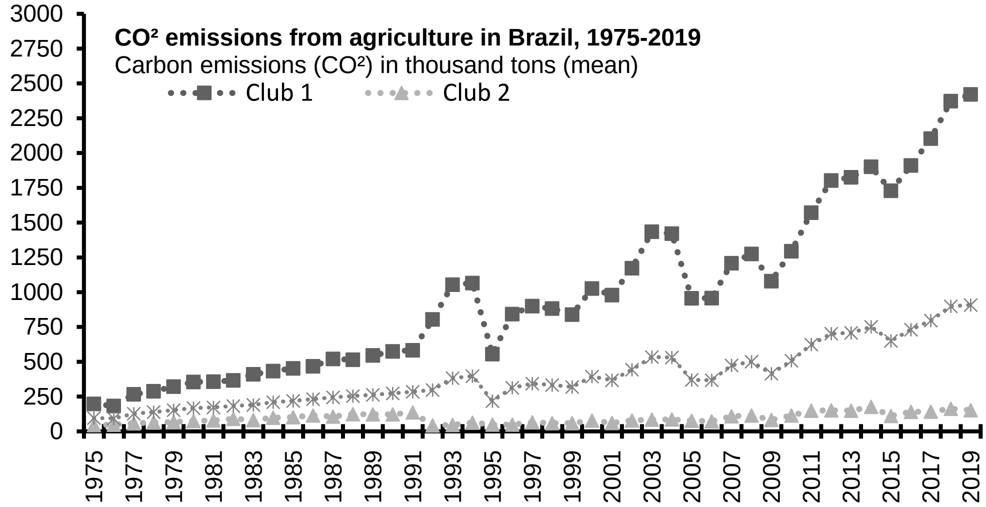
4.2 CO^2 emissions in agriculture by convergence clubs

Fig. 3 presents the average trend of CO^2 emissions from the agricultural sector, covering both the two identified convergence clubs and all Brazilian states, during the period from 1975 to 2019. As can be seen, there is a notable trend of average growth in CO^2 emissions from agriculture in Club 1. In this scenario, we note a substantial increase, from 197 thousand tons in 1975 to a significant 2,421 thousand tons in 2019, which represents an increase of more than 12 times compared to the initial average value. On the other hand, Club 2 also shows an average increase in CO^2 emissions from agriculture, from 45.9 thousand tons in 1975 to 152.4 thousand tons in 2019, which is equivalent to an increase of more than three times compared to the initial average value. Furthermore, the trajectory of Club 2 is more stable and controlled over time than that of Club 1.

The results indicate that CO^2 emissions from the agricultural sector are, to some extent, controlled in most Brazilian states. This is particularly noteworthy due to the scope of Club 2, which includes about 70% of the states in the national territory. However, on the other hand, some states that belong to Club 1 have concentrated a significant share of CO^2 emissions, making it crucial to implement specific policies to combat pollution resulting from inadequate soil management practices. These policies may include stricter environmental regulations, soil management programs, incentives and subsidies to expand conservation agricultural areas, and promotion of access to rural credit at lower interest rates for producers who commit to adopting more efficient and low-carbon agricultural technologies (Anghinoni et al., 2021). Such actions aim not only to reduce CO^2 emissions but also to promote more efficient management of natural resources, contributing to the sustainable development of food production in Brazilian territory.

To provide a more comprehensive overview of CO^2 emissions from Brazilian agriculture, we provide descriptive statistics for the convergence clubs and for all states in the sample in Table 2. Based on these statistics, we find that for the period from 1975 to 2019, the average CO^2 emissions of the sector for Club 1 are 982.7 thousand tons, with an average annual growth rate of 23%. For Club 2, the average CO^2 emissions reached about 94.85 thousand tons, with an average annual growth rate of 24.1%. Considering all states, the average CO^2 emissions in agriculture were 390.8 thousand tons, accompanied by an average annual growth rate of 23.75%. This trend of pollution in the agricultural sector is of great concern, as the Brazilian economy urgently needs to control its CO^2 emissions in order to achieve the greenhouse gas reduction targets established under the Paris Agreement (Lima et al., 2020).

Fig. 3 Average trend of CO^2 emissions from agriculture by club



Source: Prepared by the authors.

Table 2. Descriptive statistics and average growth rate

Clubs	Average growth (%)	Descriptive statistics				
		Mean	**Std. dev.**	**Median**	**Min.**	**Max.**
Club 1	23.05	982.69	898.43	780.06	3.49	5,349.68
Club 2	24.11	94.84	127.65	42.07	0.09	661.72
All states	23.76	390.79	674.38	91.87	0.09	5,349.68

Source: Prepared by the authors, with data from the SEEG.
Notes: CO^2 emissions from agriculture in thousand tons.

Next, we analyzed CO^2 emissions from agriculture for both the convergence clubs and the entire sample, comparing the periods before (1975-2004) and after (2005-2019) the implementation of the Kyoto Protocol (Table 3). [9] It is important to note that among developing countries, Brazil has voluntarily committed to reducing its GHG emissions as part of its efforts to mitigate ongoing climate change (Oliveira et al., 2019).

Table 3. CO^2 emissions from the agricultural before and after the Kyoto Protocol

Clubs	Before Kyoto		After Kyoto		Change	
	Mean	**Std. dev.**	**Mean**	**Std. dev.**	**Difference**	**Growth (%)**
Club 1	660.49	618.44	1,627.10	1,018.94	966.62	146.35
Club 2	78.71	104.17	127.10	160.30	48.39	61.48
All states	272.64	457.94	627.10	928.82	354.47	130.01

Source: Prepared by the authors, with data from the SEEG.
Notes: CO^2 emissions from agriculture in thousand tons.

Before the entry into force of the Kyoto Protocol, the CO^2 emissions from the agricultural sector for Clubs 1 and 2 were, on average, 660 thousand tons and 79 thousand tons, respectively. After the implementation of the Kyoto Protocol, the CO^2 emissions for Clubs 1 and 2 increased, on average, to 1,627 and 127 thousand tons, respectively. This represented an increase of 996 thousand tons and 48 thousand tons in the CO^2 emissions from agriculture for Clubs 1 and 2, which corresponds to a growth of 146.5% and 61.5%, respectively. Within the scope of all Brazilian states, there was a significant average increase of 354 thousand tons in the CO^2 emissions from agriculture before and after this international agreement, indicating a growth of 130%.

The remarkable increase of CO^2 emissions in agriculture underlines that the environmental sustainability of this economic activity has been largely neglected in Brazil in recent decades. The increase in pollution in the agricultural sector can also be attributed to the impressive growth that the country has registered since 2003. This period was characterized by a boom in agricultural commodity prices, triggered by the increase in global demand for food. To meet this growing demand, Brazilian producers have intensified their agricultural practices to increase crop productivity. One

[9] During the period of the Kyoto Protocol, Brazil voluntarily committed to reduce its emissions by 36.1% to 38.9% from 1990 levels. Currently, this protocol has been replaced by the Paris Agreement, as many developed countries have not ratified it as of 2005, such as the United States (Oliveira et al., 2019).

of the strategies implemented was a significant increase in the use of limestone and fertilizers to improve soil quality. This practice helped to optimize growing conditions for crops, resulting in higher yields. However, this intensification of agriculture also had a significant impact on the environment. The increasing use of limestone and fertilizers led to an increase in CO^2 emissions, moving the country away from its GHG reduction targets (Pereira et al., 2012).

Table 4 presents a comparison of CO^2 emissions from agriculture before and after the implementation of the Kyoto Protocol for the different Brazilian states. The table is organized to show the average difference in CO^2 emissions from agriculture in a thousand tons before and after the adoption of the Kyoto Protocol, ordered in descending order by the degree of emission of the Brazilian states. Analyzing the change in the average level of CO^2 emissions from agriculture before and after this international agreement, we note that only the states of Pernambuco (-56 thousand tons), Sergipe (-24.35 thousand tons), and Paraíba (-1.65 thousand tons), all belonging to Club 2, show a reduction in their emissions. On the other hand, the states of Mato Grosso (+ 2,249.68 thousand tons), Minas Gerais (+ 1,502.08 thousand tons), and São Paulo (+ 1,143.86 thousand tons), which belong to Club 1, show the greatest increase in carbon emissions from agriculture. In general, the results show that CO^2 emissions increase faster in Brazilian states where agriculture has an intensive use of technology, capital, and fertilizers.

Table 4. CO^2 emissions from the agricultural before and after the Kyoto Protocol

Clubs	State	Before Kyoto		After Kyoto		Before and After Kyoto	
		Mean	Std. dev.	Mean	Std. dev.	Difference	Growth (%)
2	PE	112.15	58.08	56.19	30.36	-55.96	-49.89
2	AL	73.79	26.40	49.44	27.69	-24.35	-33.00
2	PB	71.76	54.46	70.11	26.51	-1.65	-2.30
2	RJ	22.28	14.80	26.59	11.22	4.31	19.33
2	AP	0.52	0.33	5.32	3.01	4.80	915.80
2	RN	46.53	33.93	51.67	18.78	5.14	11.05
2	RR	1.87	1.33	10.70	4.43	8.83	473.26
2	AC	5.23	4.43	19.19	11.37	13.97	267.12
2	DF	15.98	62.21	29.97	13.62	13.99	87.51
2	AM	7.39	4.80	24.90	12.84	17.51	236.83
2	MA	165.56	57.65	183.26	158.27	17.70	10.69
2	SE	18.44	13.00	64.39	26.87	45.95	249.13
2	RO	24.27	22.55	101.96	47.38	77.69	320.07
2	ES	79.09	38.17	159.10	58.33	80.01	101.16
2	SC	322.49	118.36	449.51	94.32	127.02	39.39
2	CE	114.83	86.13	242.65	113.54	127.82	111.31
1	PA	40.93	29.06	211.33	88.96	170.40	416.31
2	PI	68.08	60.73	246.80	124.98	178.72	262.50
2	BA	266.54	108.50	496.08	169.70	229.55	86.12
1	TO	76.95	79.36	553.72	375.75	476.77	619.55
1	RS	1,037.15	321.91	1,568.47	546.33	531.31	51.23
1	PR	1,065.92	474.02	1,848.12	453.07	782.19	73.38
1	GO	631.24	448.60	1,544.50	486.33	913.25	144.67
1	MS	323.87	229.28	1,253.88	503.90	930.01	287.15
1	SP	1,240.23	690.35	2,384.10	380.49	1,143.86	92.23
1	MG	812.56	447.74	2,314.63	540.37	1,502.08	184.86
1	MT	715.51	849.90	2,965.18	1,312.96	2,249.68	314.42

Source: Prepared by the authors, with data from the SEEG.
Notes: CO^2 emissions from agriculture in thousand tons.

Our previous results show that strategies to control CO^2 emissions in the Brazilian agricultural sector are necessary, but should not be applied uniformly and deliberately. We identified two convergence clubs with different levels of carbon emissions. Therefore, government planners, policymakers, and entrepreneurs in the agricultural sector need to consider these differences in order to adopt more effective approaches to reduce CO^2 emissions. In addition, they must consider the aspects of carbon emissions in the states that are part of each convergence club. These aspects include geographic, economic, environmental, and institutional factors (Lamb et al., 2021). In Section 4.4, we provide guidance on the productive and economic characteristics of the states that are part of the convergence clubs. This will help inform the design of more assertive policies to reduce carbon emissions in the Brazilian agricultural sector.

4.3 Results of β-convergence test

The grouping algorithm reveals the presence of convergence clubs with regard to CO² emissions in the Brazilian agricultural sector. Now, we seek to analyze more specifically the β-convergence of clubs in CO² emissions, which includes the calculation of the convergence speed and half-life. When we refer to β-convergence in CO² emissions in agriculture, we are considering a theoretical framework similar to that of the income. In this framework, the richer states in agricultural production that started with higher levels of emissions have a relatively higher rate of reduction in terms of pollution over time compared to the poorer states in terms of agricultural production that started with lower levels of emissions (Pettersson et al., 2014).

To test this hypothesis, we used a model that consists of a regression with a fixed effect estimator, where the growth rate of CO² emissions in agriculture is regressed on its initial level. Therefore, we conducted the β-convergence test on CO²emissions in agriculture for the two identified clubs. If the estimated coefficient for this regression is negative and statistically significant, we can conclude that the β-convergence phenomenon exists (Runar et al., 2017; Zhu and Lin, 2020).

The results of these estimates are presented in Table 5. As expected, the estimated coefficients for the initial value of CO² emissions in agriculture are negative and statistically significant at the 1% level for each of the convergence clubs. This strongly suggests the existence of β-convergence in clubs, that is, that CO² emissions in agriculture are converging to their own stationary state in each club.

Table 5. β-convergence test for final clubs

	Club 1	**Club 2**
Coefficient	-0.300	-0.243
	[0.073]***	[0.040]***
Speed of convergence (%)	0.70	0.50
Half-Life (years)	104	128
State-fixed effects	Yes	Yes
Year-fixed effects	Yes	Yes
Adjusted-R2	0.342	0.501
Number of states	9	18

Source: Prepared by the authors.
Notes: Robust standard error in brackets. *p<0.1, **p<0.05, ***p<0.01.

The convergence speed refers to the rate at which states with lower levels of agricultural CO² emissions are approaching states with higher emission levels. In relation to the half-life, this is interpreted as half the time it takes for states to reach half the distance to their steady state in terms of CO² emissions (Pettersson et al., 2014). For Clubs 1 and 2, the estimated absolute convergence speed is 0.7% and 0.5% per year, indicating that the time required to halve the difference in agricultural CO² emissions between states with lower emissions and those with higher emissions is, on average, 104 and 128 years, respectively.

In general, the results point to a slow process of convergence in CO² emissions from the Brazilian agricultural sector. This requires immediate action if the country wants to meet its short- and medium-term GHG mitigation targets. The slowness in the convergence process can be due to several factors, such as resistance to change by agricultural producers, lack of investment in clean technologies, and reliance on limestone and urea (fertilizer) to increase agricultural productivity. In this context, long-term policies are needed to promote sustainable agricultural practices. Cooperation between states by club can facilitate the adoption of policies and best agricultural practices, and consequently accelerate the process of convergence of CO² emissions in agriculture (Amorim et al., 2023).

4.4 Drivers that affect the formation of convergence clubs

The last part of the empirical analysis of this study aims to deepen the understanding of the factors that influence the formation of convergence clubs in carbon emissions of the Brazilian agricultural sector. To achieve this objective, we use a conventional Probit model to identify the elements that influence the formation of the previously identified convergence clubs. The factors considered in the analysis of club formation are based on the studies of Liu et al. (2021) and Xu and Lin (2017) for Chinese agriculture. Thus, we focus specifically on examining the role that agricultural production factors and the production structure of Brazilian states play in the formation of convergence clubs.

The results of the Probit model are presented in Table 6. It is important to note that all coefficients are statistically significant at the 1% level. When examining the coefficients, we notice that several factors influence the formation of convergence clubs in emissions from the agricultural sector over time. Among these factors, land use, rural labor, cattle density, and industrial production stand out, all of which are associated with a lower probability of a state belonging to Club 1 (high carbon emissions). On the other hand, factors such as capital, agricultural production, rural credit, and energy consumption decrease the probability of a state belonging to Club 2 (low carbon emissions). In other words, these latter factors increase the probability of a state belonging to Club 1, which represents states converging towards high carbon emissions in the agricultural sector. In general terms, land use, labor, capital, cattle density, agricultural production, industrial production, rural credit, and energy consumption are identified as drivers for the formation of these convergence clubs.

Table 6. Regression results of the Probit model

Variables	Coefficient
Rural land use	-0.075
	[0.006]***
Rural capital	1.128
	[0.252]***
Rural labor	-1.675
	[0.157]***
Bovine density	-1.382
	[0.173]***
Agricultural output	0.772
	[0.156]***
Industrial output	-0.995
	[0.148]***
Rural credit	1.187
	[0.152]***
Energy consumption	0.570
	[0.140]***
Number of states	27
Observations	1,215
Pseudo R^2	0.705
Log pseudolikelihood	-228.19
Wald chi2	572.40***

Source: Prepared by the authors.
Notes: Robust standard error in brackets. Statistical significance: *p<0.1, **p<0.05, ***p<0.01.

This finding for Club 1 is consistent with the average concentration of CO^2 emissions from agriculture in states in the Midwest, Southeast, and South of Brazil (see Appendix Fig. B2). In these regions, the economic structure of the states is more advanced, and agricultural production is characterized by the use of modern inputs (capital and fertilizers) and agricultural technologies. On the other hand, the states that form Club 2 are mostly located in the North and Northeast regions of Brazil, where livestock farming plays an important role, and agriculture is characterized by its extensive nature and labor intensity in the field. In general, we find that the results of the Probit model are consistent with the characteristics of the states that form the convergence clubs with low and high carbon emissions in Brazilian agriculture.

5. CONCLUSIONS AND POLICY RECOMMENDATIONS

In the last decades, Brazil has experienced rapid growth in agricultural production, accompanied by significant penetration of its commodities in the world market. The country is one of the largest food producers in the world. However, economic growth based on the production and export of agricultural commodities has been accompanied by serious environmental problems, such as the increase in carbon dioxide (CO^2) emissions from soil managed, especially due to the intensive use of limestone and urea (fertilizer) to increase crop productivity. As a result, this has increasingly contributed to the country moving away from its CO^2 mitigation goals.

Differently from other developing countries, Brazil has set ambitious targets to reduce carbon emissions, both under the Kyoto Protocol, which is no longer in force, and under the Paris Agreement. However, these ambitious goals have proven difficult to achieve, as the country's economic growth is linked to the exploitation of natural resources and food production systems that do not yet meet the environmental quality standards required to address global issues such as climate change. Consequently, understanding the dynamics of CO^2 emissions from agriculture in all Brazilian states is important for the formulation of policies that contribute to achieving short- and medium-term carbon emission reduction goals. Currently, CO^2 emissions from the managed soil in the agricultural (in tons) represent the fourth-largest source of emissions in Brazil.

Considering this context, the main objective of this article was to study the convergence patterns of direct carbon dioxide (CO^2) emissions from the agricultural sector (soil managed), focusing on the states of Brazil. For this purpose, we used the convergence clubs approach developed by Phillips and Sul (2007; 2009), covering the period from 1975 to 2019 and all 27 federal units of the country. Empirical results indicate that there are two convergence clubs for CO^2 emissions from agriculture. The high emissions club consists of nine states in the Central-West, South-East, and South Brazil regions, where agricultural development is characterized by modern and technology-intensive production systems, capital, and fertilizers. In contrast, the club of low-emission states, composed of 18 states, is mainly located in the North and Northeast, where agricultural production systems are still traditional. When we compare the level of CO^2 emissions from agriculture for these convergence clubs before and after the Kyoto Protocol came into force, we find that environmental sustainability in this sector was largely neglected during the period under study.

We also conducted an analysis to explore the potential drivers of the formation of these convergence clubs. We examined the role of agricultural production factors and economic structure in the formation of convergence clubs. The results of this analysis suggest that land use, rural labor, bovine density, and industrial production are all associated with an increased probability of states forming the low CO^2 emissions club. On the other hand, factors such as agricultural production, rural capital, rural credit, and energy consumption tend to increase the probability of states forming the high CO^2 emissions club. In general, these factors are key determinants of the formation of convergence clubs in CO^2 emissions from soil management in Brazil's agricultural sector.

Based on the results of our investigation, we recommend that the Brazilian government adopt regulatory policies for the states within the high and low CO^2 emission clubs in agriculture. The creation of a regulatory environment aligned with the productive and environmental characteristics of the states belonging to each identified convergence club aims to encourage the transition to more sustainable agricultural practices in Brazilian states, with the purpose of reducing CO^2 emissions related to soil management (use of limestone and fertilizers) and promoting ecosystem preservation. As a result, it is expected that pollution control in the agricultural sector will occur, and the CO^2 mitigation targets promised by Brazil to the international community will be achieved.

Finally, we present directions for future research. We believe it would be highly beneficial to investigate whether convergence can be achieved regarding other greenhouse gases in the context of Brazilian agriculture. We also recommend that subsequent studies focus on the analysis of the convergence of CO^2 emissions at the local level, with the aim of providing more detailed information that can enrich the development of carbon emissions control policies in agriculture.

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APPENDIX A

Table A1. Description of state-level data panel, 1975-2019

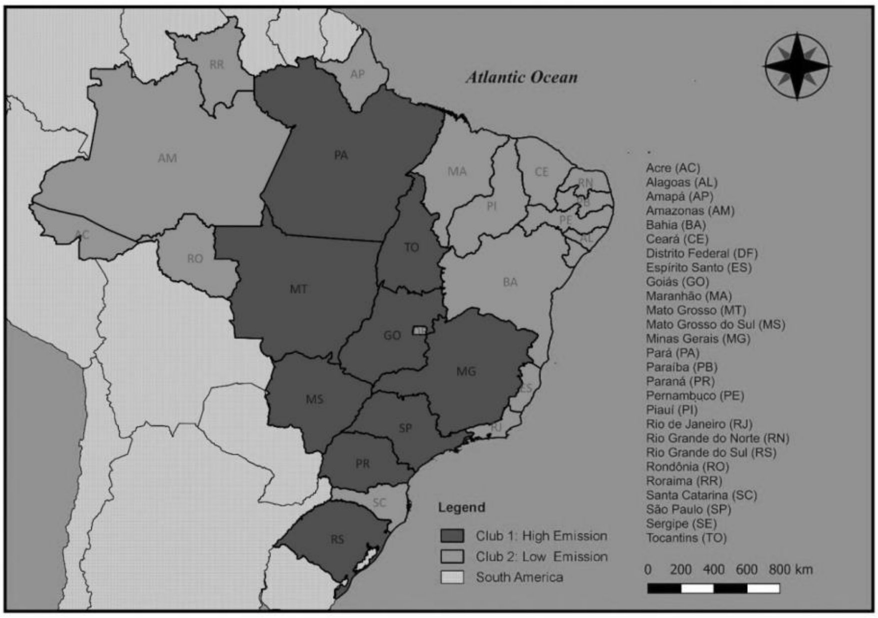
#	Description	Source
1	**Carbon Emissions:** CO² emissions from agriculture (managed soils) thousand tons.	SEEG
2	**Rural Capital:** Ratio of the number of tractors to the cultivation area.	IPEA - IBGE
3	**Rural Labour:** Ratio of the number of people employed in the rural sector to the cultivation area.	IPEA - IBGE
4	**Livestock Density:** Bovine herd per km².	PPM -IBGE
5	**Agricultural Production:** Value of agricultural production in thousand Brazilian reais at 2010 prices.	IPEA - IBGE
6	**Energy Consumption:** Electric energy consumption (MWh).	IPEA-MME
7	**Industrial Production:** Value added of industrial production in thousand Brazilian reais at 2010 prices.	IPEA - IBGE
8	**Rural Credit:** Flow of rural credit in thousand Brazilian reais.	BACEN
9	**Land Use:** Ratio of total harvested area to territorial area (%).	IPEA - IBGE

Source: Prepared by the authors.

Notes: Table A1 presents the description of the variables used in the convergence analysis and in the estimation of the Probit model. The variables from (1) to (8) are used in natural logarithm in econometric analysis.

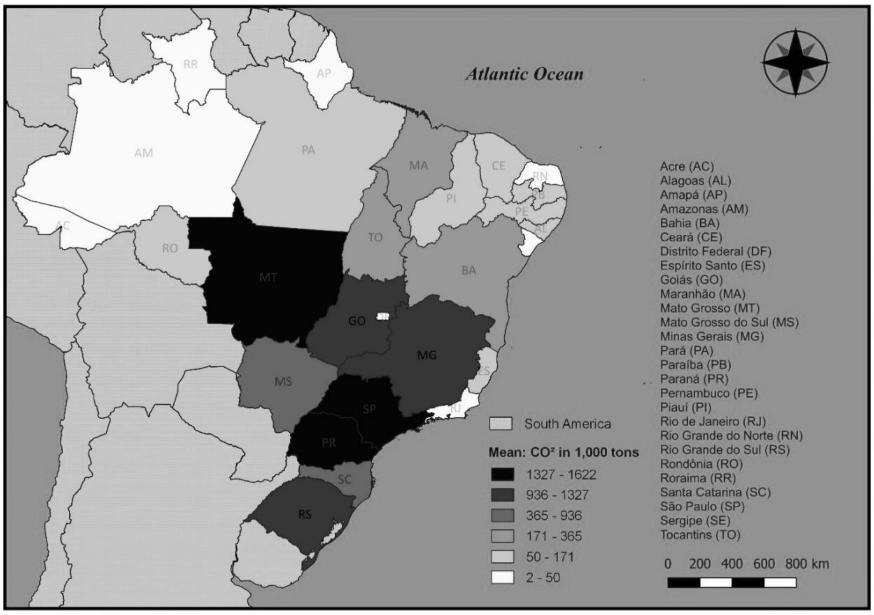
APPENDIX B

Fig. B1 Spatial distribution of convergence clubs in CO² emissions in agriculture



Source: Prepared by the authors, with data from the SEEG.

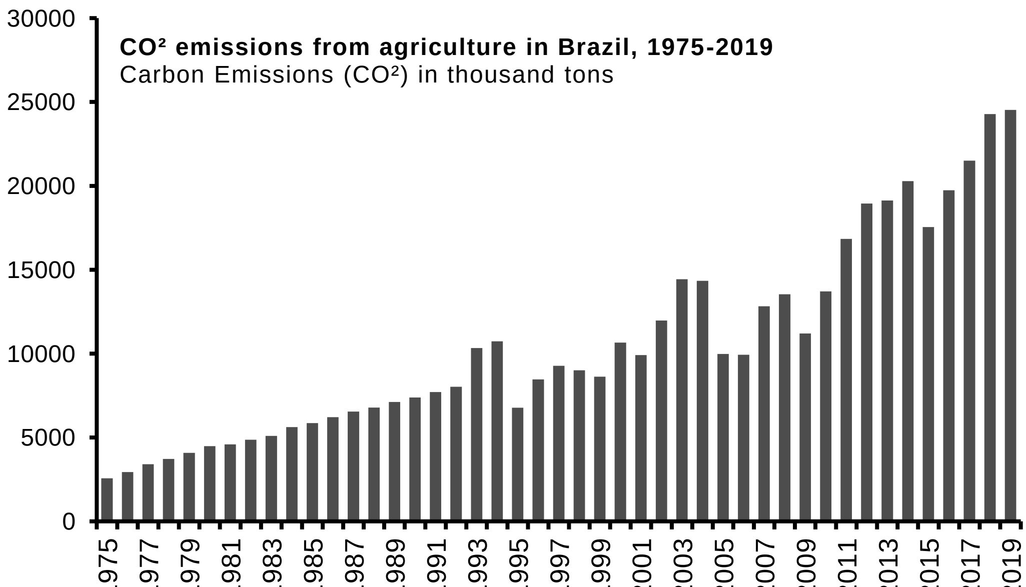
Fig. B2 Average CO² emissions from agriculture in Brazil



Source: Prepared by the authors, with data from the SEEG.

APPENDIX C

Fig. C1 Trends in CO² emissions from agriculture (managed soils) in Brazil



Source: Prepared by the authors, with data from the SEEG.