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ECOSYSTEMS

Determinants of greenhouse gas emissions by Brazilian agricultural sector

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Abstract: The agricultural sector is one of the most polluting economic activities, contributing significantly to greenhouse gas (GHGs) emissions. Brazil is one of the largest agricultural producers worldwide and plays a major role in reducing the environmental impact of this sector. Here, we aimed to determine the impact of the agricultural sector, with special attention to production, prices, and trade openness, on the short- and long-term GHGs emissions of Brazilian agriculture. Employing data from 1974 to 2019, we tested the cointegration of variables and compared the determinants of GHG emissions using Autoregressive Distributed Lag (ARDL) and Vector Error Correction Model (VECM) methods. Our results show a long-term equilibrium trend for Brazilian agricultural GHGs emissions, a result that correlates with emerging environmental compliance, and society demands the adoption of sustainable technologies, processes, and policies. In the short run, both cattle herds and Agricultural Added Value to GDP per capita showed an expected positive and significant contribution to GHGs emissions, while agricultural crop area demonstrated an inverse relationship. The trade openness index confirmed that foreign trade plays an important role in reducing GHGs emissions. The price index is not significant in our models. Both the private and public sectors have important roles in sustainable agriculture, especially in increasing system efficiency through the adoption of management and technologies that reduce GHG emissions levels.

Key words: ARDL, Brazil, cointegration, grains, pasture, VECM.

INTRODUCTION

Climate change is currently a major issue for most nations worldwide, and Greenhouse Gases (GHGs) emissions from anthropogenic actions differ between countries. According to the IPCC (2020) report, Agriculture, Forestry and Other Land Use (AFOLU) activities represented approximately 23% of GHGs emissions in the period between 2007 and 2016, and when associated with all the activities in pre- and post-farm production, it may reach 37% of net anthropogenic GHG emissions. Consequently, the adoption of sustainable production practices throughout the agricultural supply chain is essential for the private sector (Nepstad et al. 2006, Gibbs et al. 2015), whereas civil society and governments should closely monitor the actions taken (Silva et al. 2022).

The challenge of reducing GHGs emissions in the agricultural sector significantly impacts the Brazilian economy, as an international reference and one of the most important producers of soybean, maize, cotton, and coffee in vegetal production, and cattle, pigs, and chickens in livestock (FAO 2022). While a large share of its production is destinated to foreign markets, the internal market involves a large contingent of economics agents, which have large impact in Brazilian economy. Considering the agribusiness concept (Davis & Goldberg 1957), which includes the industry and services related to the agriculture, the whole sector is estimated to represent approximately 27.4% of Gross Domestic Product (GDP) in 2021 (CEPEA/ESALQ 2022).

International markets are actively demanding the use of sustainable production methods and accounting for carbon trade balance (Kim & Tromp 2021). Consequently, the reduction in GHG emissions is an important issue for the agricultural sector to reach such markets. Therefore, the agricultural sector is under constant vigilance by national and international communities, especially in the Amazon region, which is a prominent area for agricultural expansion, raising a series of other environmental problems, such as deforestation (Koch et al. 2019, Stabile et al. 2020), and loss of biodiversity (Feng et al. 2021).

Brazilian GHGs emissions are increasing over time and shifting geographically, as the agricultural frontier is expanding to new areas. The Brazilian Amazon and the Cerrado in MATOPIBA region – constituted by the states of Maranhão, Tocantins, Piauí, and Bahia covering an area of 73 million of hectares (Santos et al. 2021) – faced a substantial expansion of large scale agricultural production since the 1980s (Araújo et al. 2019, Oliveira Aparecido et al. 2023). The cropped area in MATOPIBA grew by 51% between 2012 and 2022, mainly with grains, compared to a 34% increase in Brazil as a whole. In this new agricultural frontier, the expansion of arable land, large employment of capital (machinery and equipment), technologically improved seeds, and intensive use of chemical pesticides and fertilizers have resulted in high productivity and additional GHGs emissions (Donagemma et al. 2016).

Cattle ranching is also an important economic activity and is considered one of the most important sources of GHGs emissions. The large stock of animals in most properties is managed by inefficient production systems, with the main characteristics being an extensive pasture area and low stock density (Bragança et al. 2022). Consequently, animal production makes a huge contribution to GHGs emissions through the conversion of native forests to pasture, machinery intensity use, and animals' natural emissions–. In the long term, it is expected that more sustainable models will occupy the areas currently under inefficient livestock systems, increasing productivity and adopting sustainable standards (Azevedo Junior et al. 2022, Merry & Soares-Filho 2017). However, while the current productive and institutional paradigms drive Brazilian agriculture to new regions, oriented by more intensive use of land and inputs, it is interesting to analyze how sector GHG emissions are affected by the new sustainable standards.

To explore the effects of agricultural production on GHGs emissions over time, time series analyses of cointegration and long-run effects have been employed in the literature, including the Autoregressive Distributed Lag model (ARDL) and the Vector Error Correction model (VECM) (Zafeiriou & Azam 2017, Abbasi & Riaz 2016, Asumadu-Sarkodie & Owusu 2016, Si et al. 2021) (France, Portugal and Spain.

Several studies have analyzed GHG emissions using time series worldwide, evaluating many sectors (Homma et al. 2012). Previous studies have considered the role of agriculture and livestock (Cerri et al. 2009) and cattle ranching (Bustamante et al. 2012) in Brazilian CO_2 emissions. Rüstemoğlu & Andrés (2016) compared Brazil and Russia and found that economic activities and population were relevant variables that increased CO_2 emissions. Garofalo et al. (2022) explored the effects of land-use change at the municipality level in Brazil based on spatial data and showed that current GHGs emissions are higher in the Amazon region, which is increasing agricultural and pasture areas through deforestation. Amarante et al. (2021) analyzed the relationship between economic growth, energy use and CO_2 emissions in Brazilian states with a panel data. The short- and long-run effects of CO_2 emissions were tested in Brazil for agriculture and renewable fuels (Ben Jebli & Ben Youssef 2019), whereas Raihan & Tuspekova (2022) tested CO_2 emissions with several variables, including agricultural value-added and forested areas. However, few studies employing time-series methods for Brazil focus specifically on agricultural production impacts. This study aimed to determine the short- and long-run impacts of the Brazilian agricultural sector on GHG emissions, with special attention to trade openness, production data, and prices.

MATERIALS AND METHODS

Data

To verify the impact of the agricultural sector on GHG emissions, this study employed annual time-series data from 1974 to 2019 gathered from different sources. Greenhouse gases (GHGs) emissions data from the agricultural sector were obtained from FAO (2022) in kilotonnes of CO^2 equivalent (CO2e). This variable includes emissions from CH_4 and N_2O from agriculture and livestock aggregates converted into their CO2 equivalents using the IPCC (2015) AR5 global warming potential coefficients defined in the Intergovernmental Panel on Climate Change (IPCC).

The agricultural production area (APA), measured in hectares, is the sum of both permanent and temporary crops harvested over a year and represents the vegetal production of agriculture. We used the cattle herd (CH) as a proxy for the most impacting animal activity in Brazil and measured the number (heads) of live animals. APA and CH were obtained in National Agricultural Research and National Livestock Research, respectively (IBGE 2021). Agriculture, Forestry, and Fishing Value Added to GDP (AGDP), measured in dollars, was transformed to per capita value (AGDPpc) dividing by yearly Brazil population to represent the average rural income. The trade openness index (TO) represents the openness of a national market to international trade, and was calculated as the sum of exports and imports divided by the gross domestic product (GDP) (Rafiq et al. 2016, Ben Jebli & Ben Youssef 2017). GDP, Exports and Imports, and Agricultural Added Value for Gross Domestic Product were obtained in World Bank (2022).

We also estimated an Agricultural Price Index (API) to use as an exogeneous proxy for agricultural prices in Brazil, aiming to verify if prices contribute in GHG emissions. To build the API we divided the agricultural production value (AVP) of all 69 agricultural crops available in National Agricultural Research by its produced quantity (Q), in ton, to estimate its yearly average price. We weighted each crop's average price based on the yearly crop share of the total agricultural area in Brazil to evaluate the relative importance of each crop according to its area, reducing the weight of activities with higher average prices (e.g., due to higher production costs) and low quantity produced on the index (IBGE 2021). API is the sum of each crop price weighted by the share of the area (Eq. 1). All currency variables are updated to the dollar 2015 constant (World Bank 2022), and the API is represented in Brazilian Currency 2019 prices. The descriptive statistics of the variables are given in Table I.

$$API_t = \sum_{i=1}^{70} \frac{AVP_{it}}{Q_{it}} AREA_{it} \tag{1}$$

Table I. **Descriptive statistics of variables.**

Variable	Description	Mean	Min	Max	SD
GHGs	Kilotonnes of CO² equivalent	396347.26	221223.19	528425.86	96289.88
APA	Agricultural production area, in hectares	56482194.91	41686048	80610018	10749633.50
CH	Cattle Herd, in heads.	164883480.72	92495364	218190768	39595401.40
TO	Trade openness index	0.214	0.144	0.297	0.047
AGDPpc	Agriculture, Forestry, and Fishing Value Added to GDP per capita –in dollars–	6997.32	5032.18	9247.57	1176.23
API	Agricultural price index –in Brazilian currency per ton–	1478.78	427.96	3212.43	719.26

Where the API_t is the Agricultural Price Index for each year; AVP_{it} is the agricultural production value of each culture *i* in year t; Q_{it} is the produced quantity of each culture *i* in year t; and AREA is the yearly crop's share of the total agricultural area in Brazil in year *t*.

Stationarity

To check stationary of variables, we performed the augmented Dickey and Fuller test (ADF test) and Phillips–Perron unit root test (P-P test). Schwarz information criterion was employed to determine the lag length of variables. The tests were performed with intercept and deterministic trend; only intercept; and no intercept nor trend at variable level –I(1)–, and showed non-stationary. Then we first differenced –I(1)– the variables and all become stationary (Table II).

Econometric Model

To verify the short and long-term relationship between Brazilian agricultural production and trade openness, we considered that vegetal production area and cattle heads are the main drivers of Brazilian agricultural economy, demanding more area and investments and as consequence, contribute more to GHGs emission than other activities. Agriculture, Forestry, and Fishing Value Added to GDP per capita was employed as proxy to analyze the relative economic increase in agricultural income have significant impacts in environmental issues. The Brazilian agricultural products represent a huge weight in the trade balance, the trade openness index can contribute to analyze the importance of international markets, as well as the emerging standards demanded by these markets for the agricultural sector, especially on sustainable production methods.

We employed a Cobb-Douglas function (Equation 2) to represent our model including an autoregressive lagged dependent variable. The natural logarithm of each variable was taken to express the coefficient results as elasticities (Equation 3).

$$GHGs_t = f(GHGs_{t-i}, APA_t, CH_t, TO_t, AGDPpc_t, API_t) \quad (2)$$

$$lnGHGs_t = c_0 + \beta_1 lnGHGs_{t-i} + \beta_2 APA_t + \beta_3 lnCH_t + \beta_4 lnTO_t + \beta_5 lnAGDPpc_t + API_t + \epsilon_t \quad (3)$$

Table II. Unit root test – ADF test tau statistic and P-P test.

Model	Variable	ADF test		P-P test	
		Level - I(0)	1st diff - I(1)	Level - I(0)	1st diff - I(1)
Intercept and trend	GHGs	-2.423	-5.640 *	-2.099	-6.078 *
	APA	-1.231	-5.133 *	-1.598	-7.866 *
	CH	-1.030	-4.651 *	-1.960	-5.723 *
	TO	-3.214	-5.539 *	-3.079	-6.747 *
	AGDPpc	-2.363	-5.911 *	-2.520	-7.696 *
Intercept	GHGs	-2.580	-5.186 *	-2.842	-5.500 *
	APA	0.015	-5.083 *	-0.236	-7.819 *
	CH	-1.534	-3.748 *	-2.911	-5.428 *
	TO	-1.735	-5.606 *	-1.576	-6.860 *
	AGDPpc	-1.484	-5.969 *	-1.497	-7.823 *
None	GHGs	3.077	-3.748 *	4.377	-4.008 *
	APA	2.271	-4.443 *	2.342	-7.156 *
	CH	2.732	-2.323 *	4.418	-4.405 *
	TO	-0.775	-5.594 *	-0.619	-6.644 *
	AGDPpc	-0.532	-5.951 *	-0.744	-7.656 *

Note: GHGs: Greenhouse gases emissions, in kilotonnes of CO² equivalent; APA: agricultural production area, in hectares; CH: cattle herd; TO: trade openness index; AGDPpc: Agriculture, Forestry, and Fishing Value Added to GDP per capita. * Significant at 5%.

Cointegration between variables was tested using the Johansen cointegration test (Johansen 1988) and the ARDL bounds test. We estimated the Autoregressive Distributed Lag Model (ARDL) and the Vector Error Correction Model (VECM) to verify the short and long run relationship between the variables, comparing both methods. All statistical procedures were performed using R software (version 4.1.2) (R Core Team 2023). From equation 3, the ARDL model was defined in Equation 4 and the VECM model in Equation 5. In both models we included the one year lagged Agricultural Price Index variable (API) as exogeneous variable to analyze if past agricultural prices impact the current emissions of GHGs.

$$\Delta lnGHGs_t = c_0 + \beta_1 lnGHGs_{t-1} + \beta_2 lnAPA_{t-1} + \beta_3 lnCH_{t-1} + \beta_4 lnTO_{t-1} + \beta_5 lnAGDPpc_{t-1} + \sum_{j=1}^{p}\alpha_{1j}\Delta lnGHGs_{t-j} + \sum_{j=1}^{q}\alpha_{2j}\Delta lnAPA_{t-j} + \sum_{j=1}^{r}\alpha_{3j}\Delta lnCH_{t-j} + \sum_{j=1}^{s}\alpha_{4j}\Delta lnTO_{t-j} + \sum_{j=1}^{t}\alpha_{5j}\Delta lnAGDPpc_{t-j} + API_{t-1} + \epsilon_t \quad (4)$$

Where c_0 is the constant term, Δ is the first difference operator, and the lag order of the short-run parameters (α_{ij}) for each variable are denominated by p, q, r, s, u. The null hypothesis of no cointegration for ARDL model in equation 3 $\beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0$ against the alternative hypothesis $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq 0$, calculated through F statistic in ARDL bound test.

$$\Delta lnGHGs_t = c_0 + \sum_{j=1}^{v}\gamma_{1j}\Delta lnGHGs_{t-j} + \sum_{j=1}^{v}\gamma_{2j}\Delta lnAPI_{t-j} + \sum_{j=1}^{v}\gamma_{3j}\Delta lnCH_{t-j} + \sum_{j=1}^{v}\gamma_{4j}\Delta lnTO_{t-j} + \sum_{j=1}^{v}\gamma_{5j}\Delta lnAGDPpc_{t-j} + API_{t-1} + \alpha ECT_{t-1} + \epsilon_t \quad (5)$$

The Error Correction Term (ECT_{t-1}) parameter (α) must be statistically significant and negative to the convergence of long run equilibrium. γ_{ij} are the parameters of short-term relationship with v lags (Schwarz information criterion). Granger causality test was applied in this study to check whether a variable granger causes another, meaning that the past results of one variable have power to forecast another variable outcome.

RESULTS

ARDL model

The ARDL modelling presents some advantages: i) it can be estimated if the variables are I(0), I(1) or a combination of both; ii) both short and long run parameters can be obtained simultaneously (Pesaran et al. 2001, Chandio et al. 2019). The absence of I(2) variables in our model allowed us to estimate the ARDL by testing the cointegration through the bound test approach. The optimal lag length was determined using the Schwarz information criterion. The bound test statistics reject the null hypothesis of no cointegration if the F-statistic exceed the upper bound value and accept the null hypothesis (no cointegration) if the statistic is below the lower bound. Between the lower and upper bound the test is inconclusive (Table III). The optimal model we obtained was ARDL (1, 0, 0, 1, 2).

The ARDL bound test, which the null hypothesis implies no long run cointegration, is rejected. Breusch-Godfrey LM test reject the existence of serial correlation. The Shapiro-Wilk test attest that the residuals are normality distributed. Breusch-Pagan-Godfrey accept the hypothesis of homoscedasticity of residuals. Finally, the Ramsey RESET test reject the hypothesis that the model omitted variables.

We then proceed to estimate the ARDL coefficients (Table IV). The model signs showed theoretical fundamentation. For long run estimates, the cattle herd (CH) was positive, while the Trade openness (TO) variable showed a negative sign, both coefficients were statistically significant. The error correction term (ECM) indicates the speed of adjustment to restore equilibrium over the period, and showed to be negative and significant, implying that about 84,6% of deviation from long run equilibrium is corrected in the subsequent year. In the short-run analysis, previous year GHGs

Table III. ARDL bound test and diagnostic.

ARDL Bounds test		Model Diagnostic		
Test	**value**	**Test**	**value**	**p-value**
I(0) - lower bound	3.178	Breusch-Godfrey LM Test	χ^2 = 0.236	0.791
I(1) - upper bound	4.450	Jarque–Bera test Test for Normality	χ^2 = 2.597	0.273
F-statistic	34.897	Breusch-Pagan-Godfrey test of heteroskedasticity	χ^2 = 0.557	0.822
		Ramsey RESET Test	F = 0.019	0.891

Note: Critical value of 5% for the level of significance in ARDL Bounds test.

emission and the increase in cattle herd (CH), showed positive and significant coefficients. The logarithmic form of variables expresses the results in elasticities, meaning that a 1% increase in CH or $AGDPpc_{t-2}$ would increase GHGs emission by 0.837% and 0.033%, respectively. By the other hand, lagged Trade Openness (TO_{t-1}) and the two-years lagged Agriculture, Forestry, and Fishing Value Added to GDP per capita ($AGDPpc_{t-2}$) showed negative and significant coefficients, meaning that 1% increase in the variables, reduce the GHG's emissions by 0.051% and 0.034%. Agricultural Prices Index (API) showed no significance in the ARDL model.

Vector Error Correction Model

A set of variables are cointegrated if all elements are integrated of order d and exists a non-zero vector (cointegrating vector) that is the linear combination of these variables (Enders 2014). The ADF-test and P-P test evidenced that all variables are stationary at first difference, so we tested the long-run cointegration using the Johansen cointegration test (Table V). The model contained a linear deterministic trend for the error correction term and VAR. The result confirm that exists at least one cointegrating vector between the variables of our model, as observed by the trace statistic and max-eigenvalue results.

The Johansen cointegration test confirmed that exists at least one cointegrating vector between variables, we estimated the VECM with a constant in the short and long run terms (Table VI). Serial correlation was not observed with the Lagrange Multiplier (LM) test (LM-stat = 18.179, p-value = 0.835) and Portmanteau Test for Autocorrelation (Q-Stat = 39.152, p-value = 0.717). The residuals showed a homoscedasticity distribution (χ^2 = 175.113, p-value = 0.962). Schwarz information criterion determined as one the lag length for the test.

Table IV. ARDL estimates.

Long run estimate		Short-run estimate	
Regressor	**Coefficient (std. Error)**	**Regressor**	**Coefficient (std. Error)**
AVP	0.057 (0.035)	$\Delta GHGs_{t-1}$	0.154 (0.069) *
CH	0.989 (0.044) *	ΔAPA_t	0.048 (0.030)
TO	-0.041 (0.019)*	ΔCH_t	0.837 (0.079) *
AGDPpc	0.005 (0.024)	ΔTO_t	0.016 (0.019)
Constant	-6.922 (0.578) *	ΔTO_{t-1}	-0.051 (0.018) *
		$\Delta AGDPpc_t$	0.002 (0.018)
		$\Delta AGDPpc_{t-1}$	0.0367 (0.019)
		$\Delta AGDPpc_{t-2}$	-0.034 (0.016) *
		API_{t-1}	-0.002 (0.002)
		C	-5.856 (0.722) *
		ECT	-0.846 (0.060) *

***Critical value of 5% for the level of significance.**

The Error Correction Term (ECT) in VECM, as in the ARDL model, was negative, however with lower value, meaning that 48,1% of deviation from long run equilibrium is corrected in the subsequent period. In short-run, cattle herd again is positive and significant –elasticity of 0.54%–, as well as the one-year lagged Agriculture, Forestry, and Fishing Value Added to GDP per capita ($AGDPpc_{t-1}$) – elasticity of 0.074%–. In the VECM, the APA and Trade Openness showed significant and negative signs.

We tested the causality relationship between the variables with the pairwise Granger causality analysis (Table VII). Our findings demonstrates that AVP and CH have a one-way directional causality to greenhouse cases emissions, while AGDPpc and GHGs have a bidirectional causality.

DISCUSSION

The correlation between agricultural production and GHGs emissions is an emerging topic in the literature, including studies in Europe, Asia, and Africa (Zafeiriou & Azam 2017, Chandio et al. 2019, Si et al. 2021, Asumadu-Sarkodie & Owusu 2016) (France, Portugal and Spain. gricultural production is an economically important sector in Brazil, representing a large share of the exports and GDP. In recent decades, Brazilian livestock and agricultural commodities have expanded in the Amazon and Cerrado áreas (Frey et al. 2018, Müller-Hansen et al. 2019). The extensive model and intensive use of capital have led to environmental issues, such as deforestation, chemical use and disposal, GHGs emissions, and biodiversity loss, raising doubts about the sustainability of Brazilian agricultural production.

Our study focuses on analyzing the impacts of the agricultural sector on GHGs emissions in recent decades. The time-series analysis estimates demonstrated a tendency for long-run equilibrium adjustment in GHGs emissions. In Brazil, crop production, especially agricultural commodities such as sugar cane, soybean, maize, and cotton, has an intensive use of machinery and inputs, and occurs over large areas, which may increase GHGs emissions in the short run. However, in the long run, environmental regulation (Trancoso 2021) and market pressures (Gibbs et al. 2015) constrain economic agents from adopting technologies to increase crop efficiency, adopt better management practices, preserve natural biomes, and adjust GHGs emissions through the implementation of sustainable systems. The VECM results demonstrate a negative sign for agricultural production areas. Our results corroborate the findings of Ben Jebli & Ben Youssef (2019). The authors suggested a more efficient use of energy in the agricultural sector. We argue that, in addition to such finding, the results may express the effects of markets, government, and social pressure on the adoption of sustainable

Table V. Johansen cointegration test.

Cointegration vectors	Trace statistic	Maximum Eigenvalue
None	77.892 *	34.308 *
At most 1	43.583	19.539
At most 2	24.045	16.060
At most 3	6.985	6.666
At most 4	0.319	0.319

***Critical value of 5% for the level of significance.**

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practices, although in a limited way, as the Granger causality shows a unidirectional causality with GHGs emissions. On the other hand, the agricultural price index, as an exogenous variable, showed no significance in either model.

The largest share of crop production are agricultural commodities driven by exports, which have expanded in recent decades. Until the 2000s, the main increase occurred in the Cerrado areas, while in recent years, the Amazon and MATOPIBA regions were the main spots to increase crop areas. The production systems in these export-driven crops are subject to following the most recent standards of sustainable agriculture imposed by foreign markets, and it is expected that GHGs emissions in this area will reduce over time. To accomplish these standards, it is important that public policies, such as the Low Carbon Agriculture program, and private sector accords incentivize sustainable systems (Costa Jr. et al. 2019).

Table VI. Coefficients of VECM.

Long run estimate		Short-run estimate	
Regressor	**Coeficient (Std. Error)**	**Regressor**	**Coeficient (Std. Error)**
$GHGs_{t-1}$	1	$\Delta GHGs_{t-1}$	-0.077 (0.192)
AVP_{t-1}	-0.091 (-0.035) *	ΔAPA_{t-1}	-0.168 (0.074) *
CH_{t-1}	-0.913 (-0.038) *	ΔCH_{t-1}	0.540 (0.236) *
TO_{t-1}	-0.017 (-0.017)	ΔTO_{t-1}	-0.008 (0.029)
$AGDPpc_{t-1}$	0.028 (-0.021)	$\Delta AGDPpc_{t-1}$	0.074 (0.026) *
C	5.816	API_{t-1}	-0.003 (0.003)
		C	0.036 (0.020)
		ECT	-0.481 (-0.237) *

*** Critical value of 5% for the level of significance.**

Table VII. Granger causality test.

Null hypothesis	Test statistics	p-value
lnAVP lnGHGs	5.032	0.025 *
lnCH lnGHGs	5.556	0.018 *
lnTO lnGHGs	0.235	0.628
lnAGDPpc lnGHGs	7.520	0.006 *
lnGHGs lnAVP	1.368	0.242
lnGHGs lnCH	0.571	0.450
lnGHGs lnTO	0.464	0.496
lnGHGs lnAGDPpc	4.309	0.038 *

*** Critical value of 5% for the level of significance. means the causality direction.**

Animal production, especially cattle ranching, is more strongly correlated with environmental issues than crop production. The extensive cattle ranching system occurs mainly through the conversion of forested areas to pastures (Stabile et al. 2020). The short-run estimates consistently demonstrated the positive effect of cattle herds on GHG emissions in the VECM and ARDL models. Cattle ranching is pointed as an inefficient activity in Brazil, which demands extensive land use and low production (Sparovek et al. 2018, Azevedo Junior et al. 2022), resulting in a lower stocking ratio (heads per hectare) (Pacheco & Poccard-Chapuis 2012). This inefficiency persists as cattle ranching growth in recent decades has mainly occurred due to area increase (to support more animals) than intensification (Fearnside 2005). Cattle herds have an indirect effect on GHGs emissions due to the substitution of forests with pasture to support more animals without technical progress, and a direct impact through natural GHGs emissions (Ribeiro-Filho et al. 2020).

Agriculture, Forestry, and Fishing Value Added to GDP per capita is a proxy for the impact of average rural income on Brazilian GHG emissions. Our results followed previous researches that already correlated agricultural added-value to GDP with positive effects over GHGs emissions in short-term (Zafeiriou & Azam 2017, Czyżewski & Michałowska 2022, Sharma et al. 2021, Khattak et al. 2020) (France, Portugal and Spain. Castro et al. (2018) also found that GDP growth increase CO_2 emissions, however, in a given certain level the emissions tends to reduce, and then in a subsequent level raise again. Granger causality also indicated bidirectional causality, demonstrating that the agricultural sector growth has an important and significant impact on GHGs emissions, and vice versa. Our results are similar to those of Amarante et al. (2021), who pointed out the two-ways causality between economic growth and CO_2 emissions in Brazil.

However, the trade openness index showed a negative correlation with GHGs emissions in the long term in both models, demonstrating the importance of how international pressure affects supply chains. The impact of oilseed and cattle production on GHG emissions was analyzed by Pendrill et al. (2019), and the authors accounted how the international trade is driving tropical deforestation. Ermgassen et al. (2020) studied the environmental footprinting in exporting Brazilian beef sector, identifying that economic agents in this sector vary substantially in environmental risks and standards, mainly between consolidated and expanding regions in cattle production.

Foreign trade may be subject to environmental compliance imposed by importing countries. Non-sustainable production systems reduce the insertion of agricultural products in international markets. Considering that the Brazilian agricultural sector has a large dependence on foreign trade, private mechanisms are essential in guiding actors to adopt sustainable practices in addition to police enforcement. However, the increasing demand for agricultural products may encourage production in unsustainable paths (DeFries et al. 2010)

Even though policies and government actions such as command and control, fines, and monitoring discourage agents from practicing non-sustainable systems, these institutions have reached some limitations in enforcing agents in recent years (Azevedo et al. 2017), and have raised the importance of the private sector in reducing the environmental impact of agricultural activities. Some examples of these actions are the Soy Moratorium (Gibbs et al. 2015), which has prohibited soybean commercialization from illegally deforested areas since 2008, standards for beef production (Nepstad et al. 2006), and water use certification in Brazilian sugarcane production (Brauman & Viart 2016). C Converging to international demand for sustainable production, policies should go beyond enforcement of economic agents, incentivizing the private sector to insert standards throughout the supply chain, focusing on GHGs emissions.

CONCLUSIONS

The emission of GHGs by agriculture is a vital issue because this sector accounts for a large share of the total emissions. Here, we aimed to verify the short- and long-run dynamics of the agricultural sector with respect to Brazilian GHGs emissions in recent decades. The time-series model indicated a tendency of long-run equilibrium in GHGs emissions, which is consistent with the growing pressure on sustainability standards and government regulations. In the short term, cattle herds showed a strong and positive relationship with GHGs emissions. In addition, the expansion of pasture over new arable lands originating in forested areas contributes to this net emission, phenomena that occur more intensively in the Brazilian Amazon. Crop production, in turn, had less impact on GHGs emissions in the short run.

We highlight the role of foreign trade as a mechanism to induce sustainable practices in the agricultural sector. The trade openness index negative signal reinforces that to access international markets, the entire supply chain must follow sustainable standards, contributing to a reduction in GHGs emissions, mainly for the most relevant agricultural commodities. The price index did not show a significant effect on GHG emissions.

To attain more sustainable development paths and meet the international agenda for reducing GHG emissions, the Brazilian agricultural sector must develop new mechanisms, including public policies that support innovation and incentives for private sector and agricultural supply chains involvement, particularly in the Amazon and MATOPIBA regions, which are the primary areas for agricultural expansion in Brazil and also crucial for environmental conservation.

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