Corn ethanol expansion in Brazil: Are volatility interconnectedness changing?

Daniel Henrique Dario Capitani
University of Campinas, Brazil
E-mail: danieldc@unicamp.br

Luiz Eduardo Gaio
University of Campinas, Brazil
E-mail: luizgaio@unicamp.br

Fabio Mattos
University of Nebraska, Lincoln, NE
E-mail: fmattos@unl.edu

Rodrigo Lanna Franco da Silveira
University of Campinas, Brazil
E-mail: rlanna@unicamp.br

José César Cruz Junior
Advance Trading Inc, Bloomington, IL
E-mail: ccruz@advance-trading.com

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INTRODUCTION

Brazil is a traditional global producer and consumer of sugarcane-based ethanol. From 2000 to 2014, sugarcane cropland increased by 114%, and ethanol production increased by approximately 170%. In the past years, Brazilian ethanol production has been oscillating from 30.5 to 35.6 billion litters a year, which made the country the second largest producer in the world after the U.S. (UNICA, 2023). Despite the relevance of sugarcane for biofuel production, Brazil has experienced a dramatic increase in corn-based ethanol production since the late 2010s (Eckert *et al*., 2018; Silva and Castañeda-Ayarza, 2021; Colussi *et al*., 2023). Corn ethanol plants are located throughout the Brazilian states of Mato Grosso, Mato Grosso do Sul, and Goiás, in the nation's Center-West, whereas sugarcane ethanol plants are mostly concentrated in the southeast (53.8%) and Center-West (35.2%). Corn ethanol increased from less than 100 million liters in 2014/2015 to 4.4 billion liters in the 2022/23 crop year. Currently, corn-based ethanol represents 14,2% of the country's production (UNICA, 2023).

The growth in corn-based ethanol is explained by the increase in the corn second crop ("winter crop") in the past decades, which is concentrated in the Center-West area and accounts for approximately 63% of Brazilian total production. The corn second crop is harvested from June to August, and increased from 0.98 billion bushels in 2004 to 3.1 billion bushels in 2022, making Brazil the third largest producer in the world (CONAB, 2024).

From the beginning of the 2000s, the growth of the ethanol industry in Brazil motivated several studies that address a range of questions, from agricultural land use to trade agreements, the impacts of policies and regulations on the domestic fuel market, and the changing price relationships between ethanol and related markets. Specifically, most studies on price connections and volatility transmission have focused on the linkages between sugarcane ethanol, sugar, and gasoline prices (Hallack et *al*., 2020; Palazzi *et al*., 2022). Some of these studies examined the impact of federal intervention on gasoline prices from 2011 to 2016 (Drabik *et al*., 2015). Other studies have analyzed the connections between food commodities and ethanol prices in the international market, especially in the U.S. (Quintino *et al*., 2021).

Overall, the findings of these studies indicated a significant connection between ethanol, sugar, and gasoline prices. The linkages between sugar and ethanol are explained by the fact that both commodities result from the sugarcane crush, where mills need to choose the

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output mix during the harvest. The relationship between ethanol and gasoline is derived from the relative substitution between hydrous ethanol and gasoline, and the complementarity between anhydrous ethanol and gasoline, because of the Brazilian mandate for a blend of 27% of anhydrous ethanol in gasoline. In addition, U.S. and Brazilian ethanol prices have shown weaker connections, even after the expansion of U.S. production.

The literature in this field has focused on discussing ethanol price discovery in U.S. and Brazil and its linkages with other domestic and global markets. The large growth of ethanol from corn in Brazil opens new opportunities for research as it created regional markets in Brazil that use different inputs and have their own dynamics. For example, sugarcane is harvested once a year, stays in the domestic market and is used to produce ethanol and sugar. On the other hand, corn is harvested more than once a year in Brazil, some is exported and some stays in the domestic market, and can be used to produce ethanol and food products, as well as feed livestock.

The objective of this study is to examine the dynamic connectedness between regional ethanol and corn prices in Brazil. First, we take Sao Paulo as the central market and explore the degree of price leadership relative to regional ethanol markets in the Center-West (Mato Grosso and Goiás). We focused on Sao Paulo because sugarcane ethanol is mostly located in this state, as long as the largest refineries and terminals in the country. For this analysis, we also consider sugar prices in Sao Paulo because of their connection to sugarcane ethanol prices. Second, we test the dynamic connectedness between regional corn spot prices in the Center-West and the regional ethanol prices. The idea is to capture whether the burgeoning ethanol industry in the Brazilian Center-West affected the dynamics of ethanol and corn prices in Brazil. For this analysis, we also consider soybeans prices in Center-West because of their connection to corn prices. The regional markets in consideration are Rio Verde, Sorriso, Rondonópolis and Triangulo Mineiro.

The market dynamic connectedness are estimated using the Time-Varying Parameter Vector Autoregressive Model (TVP-VAR) model with the specifications proposed by Antonakakis *et al.* (2020). This technique aims to overcome some of the limitations of the original approach by Diebold and Yilmaz (2012). The model is based on the idea that commodity price series are interconnected, and that these interconnections can change over time. TVP-VAR captures the changes in the interconnections between commodity markets, and thus provides a better understanding of how they react to certain events, such as corn ethanol expansion (Balcilar *et al.*, 2021; Mishra *et al.*, 2023).

Overall, our findings can offer new insights into the debate over ethanol price discovery in Brazil by providing empirical evidence on regional information flow across traditional markets that sugarcane ethanol is predominant, and new areas where corn ethanol has been expanding. This is innovative research on the ethanol market, both in the method employed and in the measurement of regional ethanol markets that have been explored in the literature. For the U.S. market, only Geverni *et al*. (2023) explored similar points to explain the interconnectedness between ethanol markets. In addition, the understanding of new dynamics in ethanol price discovery in Brazil can shed light on new elements for the analysis of the U.S. and Brazilian ethanol dynamic connectedness.

BACKGROUND

Ethanol production in Brazil

Ethanol production has been disseminated in Brazil over the last century and has presented two positive outbreaks (Gonçalves et al., 2023). The Federal Alcohol Program (ProAlcohol) established incentive policies for sugarcane-based hydrous ethanol production from 1975 to the early 1990s. The second outbreak occurred after the production of the bi-flex fuel vehicle technology in 2003. In this cycle, sugarcane croplands have increased from five million hectares to nine million hectares (CONAB, 2024). The 2016/17 crop had the largest harvest area, of 9,05 million hectares. The croplands expanded around the traditional areas in the southeast (mainly São Paulo state) and to new boundary areas in the Center-West, as illustrated in Figure 1.

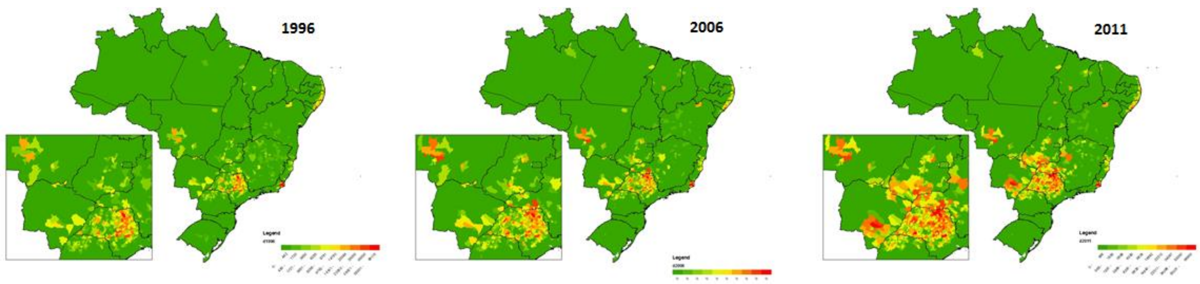

Figure 1 – Sugarcane expansion in Brazil – 1996, 2006 and 2011, by municipalities
Source: CTBE/CNPEM (2013).

According to Conab (2024), in 2005/06, 64% of the country's croplands were located in the traditional area of the Southeast region, 18,4% in the coastal area of the Northeast region, and 9.4% in the expansion area of the Center-West region. Currently, considering the geographical dynamics of sugarcane expansion, 62% of sugarcane croplands are located in southeastern Brazil. Sao Paulo corresponds to 50% of the country's production area. During this period, the Brazilian Centrer-West represented 21.8% of the total sugarcane cropland (11.6% in Goiás, 7.8% in South Mato Grosso, and 2.4% in Mato Grosso). The Northeast reduced to 10.2% of the total area.

Sugarcane expansion results in a significant increase in ethanol production. In the past decade, an average of over 50% of the sugarcane production mix has been directed towards ethanol production (UNICA, 2023). Ethanol production expanded from to 10.6 billion litters in 2000/01 to 31.2 billion litter in 2022/23 crop year. During this period, hydrous ethanol accounted for a large share of the country's ethanol production, changing from 46% to 57% of the biofuel production. During this period, the amount of anhydrous ethanol in the gasoline increased from 20% to 27% (UNICA, 2023).

In the past two decades, Brazil has also experienced a significant increase in soybean and corn croplands, mostly in the Center-West region. Considering the climatic conditions in some parts of the country, such as the Center-West, corn can be harvested in summer and winter (Mattos & Silveira, 2018). Thus, farmers can improve land rotation between soybean (summer) crops and corn winter crops (second harvest corn). From 2010/11 to 2022/23, corn production expanded from 57.4 million tons to 131.8 million tons. The winter crop share rose from 22.5 million tons in 2010/11 to 102.4 million tons in 2022/24. The share of corn production in Brazil has increased from 39.2% to 77.7%. In the Center-West, this share increased from 30.1% to 58.7% during the same period.

Such an increase in both corn and sugarcane croplands in the Brazilian Center-West over this period helps to create a positive scenario for corn-based ethanol production in this area. At late 2010's, the production expanded from 0.08 billion litters in 2014/15, to 4.4 billion litters in 2022/23, leading corn ethanol to represent 14.2% of Brazilian ethanol production (Figure 2). To reach this production, the corn production destined to ethanol production variated from less 0.3 million tons to 10.2 million tons, which represented 7.6% of the Brazilian corn production in 2022/23, or 10% of corn winter harvest (Itau BBA, 2023). According to UNICA (2023) and UNEM (2024), corn-based ethanol is expected to reach up to 30% of this biofuel production in Brazil by 2030.

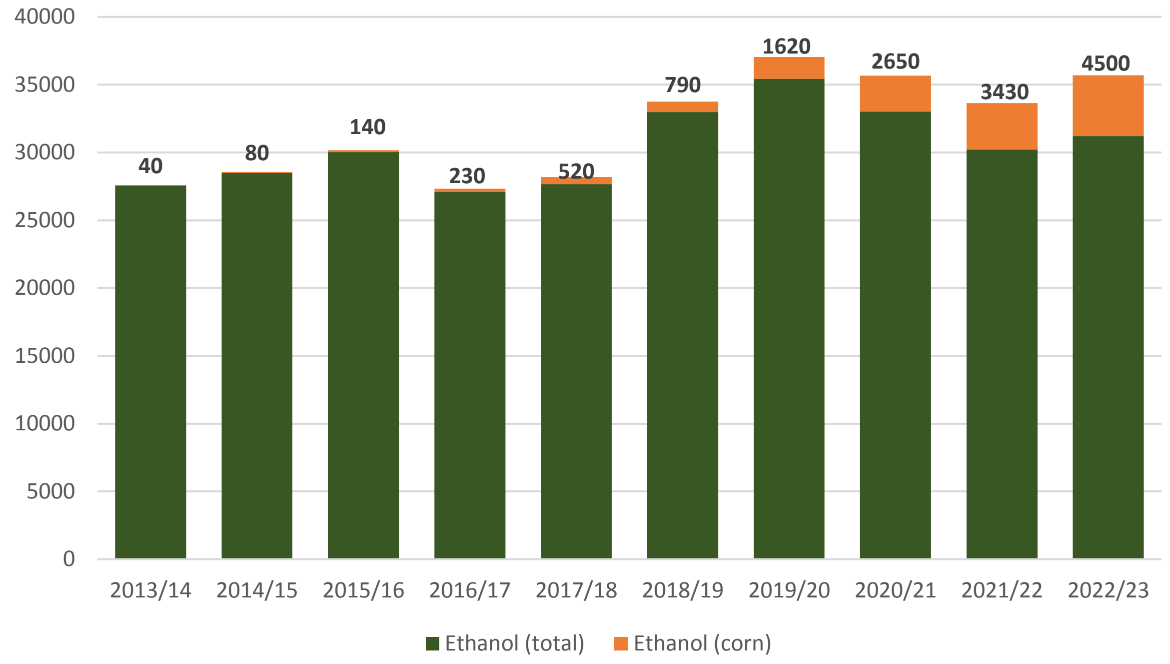

Figure 2 – Ethanol production (total) and corn-based ethanol production in Brazil (bi litters)
Source: UNICA (2024).

This production is mostly concentrated in the Center-West region. In 2023, 12 corn-based ethanol mills were operating in Brazil, of which 11 were located in the Center-West (eight in the state of Mato Grosso, two in South Mato Grosso, and one in Goiás). Additionally, there were eight more mills that exhibited flex operations (sugarcane and corn), seven of which were located in the Center-West (four in Goiás and three in Mato Grosso).

Figure 3 illustrates the regional distribution of this production. Considering both corn and flex (sugarcane and corn) distilleries, biofuel production is concentrated in the North and Southeast of Mato Grosso state (region of Sorriso and Rondonópolis, respectively), in Southern Goiás (region of Rio Verde), and in the area of Dourados in South Mato Grosso. These regions are traditional corn and soybean producers. In the Rio Verde area, sugarcane croplands expanded beyond grain production in the late 2000s, which explains why this region has many flex-operating mills.

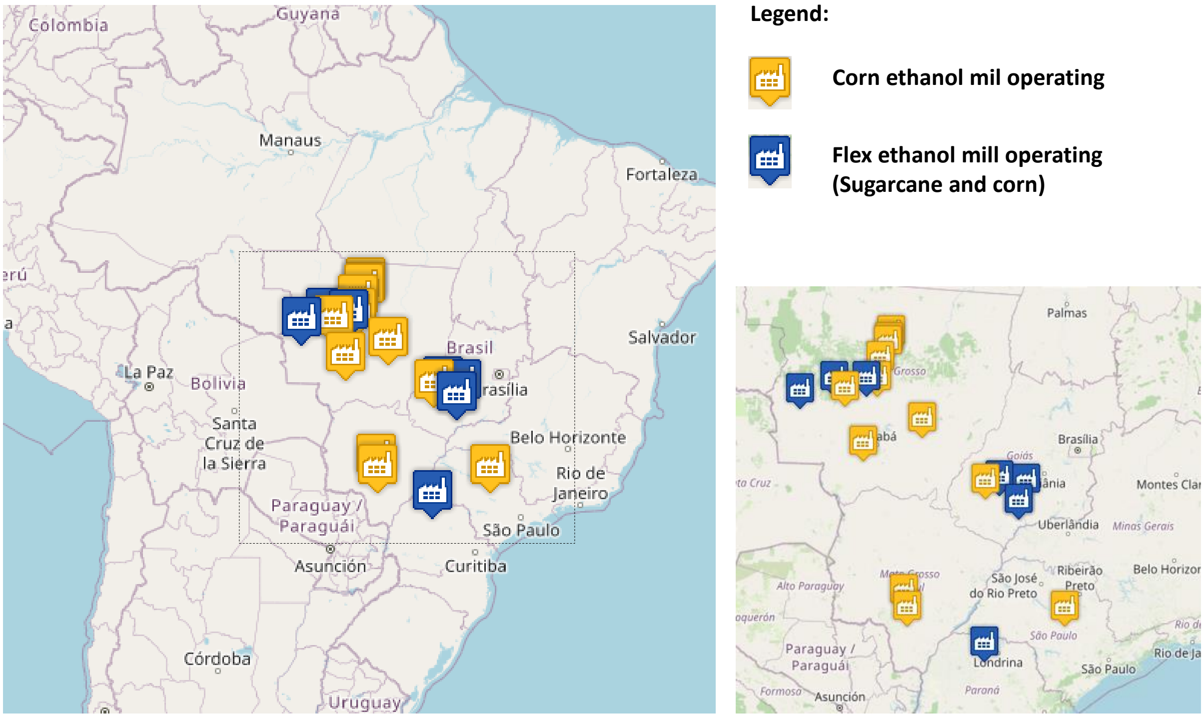

Figure 3 – Operating mills producing corn based ethanol in Brazil, 2023.
Source: RPANews (2024).

According to Gonçalves et al. (2023), the integrated production of corn- and sugarcane-based ethanol is positive for the country's long-run biofuel agenda. The flex system allows for the dynamization of biofuel production and reduces the feedstock price risk for ethanol distilleries. In addition, this production system is positive for consumers, as it reduces the seasonality of biofuel production, allowing a regular supply over a year. Colussi et al. (2023) also pointed to the benefits of the corn second harvest in the Center-West and the significant feedstock volume to these mills. Eckert et al. (2018) highlight the easy availability of corn in the country, as well as the costs and technical efficiency for the ethanol production in comparison to other feedstocks (e.g., wheat, cassava and beats).

Silva and Castañeda-Ayarza (2021) indicated the economic potential of corn-based ethanol for Brazilian biofuel production, and the country's strategic position to supply international markets. Additionally, the growth in corn production across the country can improve the feasibility of ethanol production in distant locations. However, they pointed out the possibility of negative effects from federal intervention in energy markets, which can reduce mill revenues, as pointed out by Drabik *et al*. (2015).

Volatility transmission in biofuels markets

The peaks in food commodity prices in the 2006-2008 period generated a large number of studies examining the possible causes. The literature points out some factors that contribute to these price movements. For example, demand growth from developing countries, production shortfalls, U.S. monetary policy, energy prices, and an increase in biofuel production (Irwin & Good, 2009; Zhang *et al*., 2010; Serra & Zilberman, 2013; Serra, 2011; Vacha *et al*., 2012; Kristoufek *et al*., 2014; Cabrera & Schulz, 2016; Saghaian *et al*., 2018). The growing importance of biofuels has guided new studies to examine price and volatility linkages between biofuels, energy, and agricultural commodity markets, as well as encouraging research interested in the dynamics of biofuel price discovery and integration between the most relevant markets, such as the U.S and Brazil, when considering ethanol production.

Previous studies on the U.S. market have found that gasoline and corn partially explain domestic ethanol prices, while ethanol prices may only have short-term effects on agricultural prices (Zhang *et al*., 2010; Serra *et al*., 2011). Kristoufek *et al*. (2016) observed a co-movement in the time-frequency scale from corn to ethanol prices. Several studies have examined biofuel and commodity linkages after–2006-2008 periods, pointed out that energy markets have been causing shocks in biofuel prices and driving volatility transmission (Trujillo-Barreras et *al*., 2012; Vacha *et al*., 2013; Cabrera & Schulz, 2016; Saghaian *et al*., 2018; Balcilar *et al*., 2021; Dmytrów *et al*., 2021; Palazzi *et al*., 2023). Gerveni *et al*. (2023) investigated the degree of price volatility connectedness in major regional markets in the U.S. and found that Chicago is the market that influences other local markets because of its influence as a trade terminal.

Rapsomanikis and Hallam (2006) conducted the first study involving price analysis of the Brazilian biofuel market using non-linear versions of error-correction models to understand sugar-oil and ethanol-oil relationships, finding that crude oil drives the long-term prices of ethanol and sugarcane in Brazil. A similar study by Balcombe and Rapsomanikis (2008) investigated the long-term relationship between ethanol, sugar, and oil prices. Their findings pointed out the influence of oil prices on ethanol and sugar prices as well as the effect of sugar prices on domestic ethanol prices.

Forthcoming studies have identified a connection between gasoline, ethanol, and sugar prices in Brazil. Bentivoglio *et al*. (2016) showed that gasoline and sugar shocks affect ethanol prices in the country. However, they did not find an opposite effect. Kristoufek *et al*. (2016), Dutta (2018), and Lima *et al*. (2019) reported similar findings. The interaction between corn and ethanol prices in Brazil has not been evaluated in previous studies. Capitani (2018) tested the price dynamics among ethanol, agricultural commodities (including grains), crude oil and exchange rate in Brazil. This study suggests that corn is strongly associated with soybean price.

Ethanol is only connected to sugar prices. Additionally, exchange rate and crude oil explain agricultural price movements domestically, demonstrating the importance of the macroeconomics conjuncture and the dynamics of international energy markets.

Hallack *et al*. (2016) pointed to bicausality between gasoline and ethanol prices in Brazil until 2016. However, after 2016, their findings indicated that crude oil and gasoline caused domestic ethanol prices. Lima *et al*. (2019) Palazzi *et al*. (2022) show that the dynamics of international energy prices affect the volatility of biofuel prices in Brazil.

The integration between the Brazilian and U.S. ethanol markets has been evaluated in several studies (e.g. Hernandez *et al*., 2020; Quintino *et al*., 2021; Janda *et al*., 2022). Hernandez *et al*. (2020) observed the existence of a long run relationship, and the effect from Brazil to U.S. Their study did not observe a short-run relationship. Quintino *et al*. (2021) applied two fractal methods and suggested a positive relationship between both markets. However, they did not find directional causality from one market to another. Janda *et al*. (2022) examined the volatility transmission in the U.S., Europe and Brazilian biofuels markets. Their findings did not indicate a significant convergence between them. Drabik *et al*. (2015) and Saghaian *et al*. (2018) have reported similar results.

METHODS AND DATA

To investigate the connections between markets and regions, we utilize negative and positive absolute returns and apply the connection technique related to TVP-VAR to adjust the involved volatility transmissions. The TVP-VAR approach is an adapted version of the traditional VAR approach, which is frequently used in financial literature. The linear version of the VAR model is described as equation 01:

$$y_t = c + B_1 y_{t-1} + \cdots + B_2 y_{t-p} + \varepsilon_t \qquad (01)$$

where y is a K × 1 dimensional vectors with K variables at time t and order p. $\boldsymbol{B}$ represents the K × K matrices of the coefficients.

TVP-VAR methodology was used for the analysis. This method combines the Diebold and Yilmaz (2012) and Koop and Korobilis (2014) propositions, with the approach proposed by Antonakakis *et al.* (2020). This technique, known as the Time-Varying Parameter Vector Autoregressive Model (TVP-VAR), aims to overcome some of the limitations of the original approach by Diebold and Yilmaz (2012). Studies by Mishra *et al.* (2023) and Balcilar *et al.* (2021) are examples of TVP-VAR applications for the commodity financial market.

The TVP-VAR model proposed by Antonakakis *et al.* (2020) is an econometric model that allows the estimation of parameters that vary over time in a system of vector autoregressive equations (VAR). Unlike traditional VAR, in which the parameters are fixed over time, TVP-VAR recognizes that the relationships between variables can be subject to structural changes over time. TVP-VAR allows the analysis of connectedness between commodity markets in crisis periods.

The TVP-VAR model with a lag order of one is estimated following the Bayesian Information Criterion (BIC), as per equation 02:

$$\boldsymbol{y}_t = c + \boldsymbol{B}_t y_{t-1} + \varepsilon_t \varepsilon_t \sim N(0, \Sigma_t) \tag{02}$$

$$vec(\boldsymbol{B}_t) = vec(\boldsymbol{B}_{t-1}) + v_t v_t \sim N(0, R_t) \tag{03}$$

where $\boldsymbol{y}_t$, $\boldsymbol{y}_{t-1}$, and ε_t are K × 1 dimensional vectors, and $\boldsymbol{B}_t$ and Σ_t are K × K dimensional matrices. $vec(\boldsymbol{B}_t)$ and v_t are $K^2 \times 1$ dimensional vectors, and R_t is a $K^2 \times K^2$ dimensional matrix. This model allows the parameters $\boldsymbol{B}_t$ to be time-varying, which also allows the assessment of the relationship between commodity series over time. The disturbance terms ε_t are assumed to have equal variance and follow a normal distribution with a mean of zero and time-varying covariance matrix Σ_t, which, according to Mishra *et al.* (2023), results in market fluctuations and investment risk.

According to Helmi *et al.* (2023), to compute the dynamic interactions between variables, the variance-covariance matrix of the residuals Σ_t is decomposed as follows:

$$\Sigma_t = A_t^{-1} H_t (A_t^{-1}) \tag{04}$$

where A_t is the lower triangular matrix that externalizes the contemporaneous relationships and H_t is a matrix containing stochastic volatilities on the diagonals.

The model is based on the idea that commodity price series are interconnected, and that these interconnections can change over time. The TVP-VAR captures the changes in the interconnections between commodity markets and thus provides a better understanding of how they react to crisis events (Balcilar *et al.*, 2021; Mishra *et al.*, 2023).

According to Antonakakis *et al.* (2020), one of the main advantages of the TVP-VAR approach is its lower sensitivity to outliers, which contributes to a more accurate estimation of the model parameters. Furthermore, this technique does not require an arbitrary period window, which is a limitation of the original approach. Instead, we estimate the TVP-VAR model using the Bayesian Information Criterion (BIC) with a lag of one order. When estimating a TVP-

VAR, Bayesian inference techniques or recursive filtering methods are commonly used to obtain estimates of time-varying parameters, such as the Kalman filter. These estimates allowed us to track structural changes and capture the dynamic effects that may occur during different periods.

Therefore, we apply the TVP-VAR methodology together with the expanded connectedness technique proposed by Balcilar *et al.* (2021). This allows us to overcome the limitations of the original approach by Diebold and Yilmaz (2012) by obtaining more accurate parameter estimates and a more comprehensive analysis of the interconnection between economic variables.

Data

The dataset consists of the weekly wholesale spot prices of corn, soybean, and ethanol in Brazil from January 2014 to April 2024. The sample consisted of 537 observations, except for the Rondonópolis region, for which data were available from July 2015 to April 2024 (457 observations). To improve the analysis, we considered a two-period sample. The first was conducted from January 2014 to June 2019. The second period was from July 2019 to April 2024. The first period represents the moment when corn-based ethanol production in Brazil was less than 0.8 billion litters for a crop year. In the second period, production exhibits a significant increase and the volume exceeds 1.6 billion litters.

Ethanol prices consisted of state price indicators for Goiás, Mato Grosso, and Sao Paulo. We also considered sugar prices in Sao Paulo because of their close connection with the local sugarcane-based ethanol prices. Sao Paulo ethanol and sugar series were considered because the state is the largest sugarcane (and ethanol/sugar) producer and can influence ethanol volatilities dynamics in other regional markets.

For corn, we considered the major production regions or corn-based ethanol over the Brazilian Center-Wes. This region also contains 18 of the 20 corn ethanol mills in the country, including flex distilleries. For that, we considered the regions of Rio Verde (state of Goiás), Sorriso (state of Mato Grosso), Rondonópolis (state of Mato Grosso), and Triangulo Mineiro (state of Minas Gerais, in the borderline of Goiás state and close to Rio Verde).

Mato Grosso ethanol prices were considered in the analysis of the regions of Sorriso and Rondonópolis. Goiás ethanol prices were considered in the analysis of Rio Verde and Triangulo Mineiro. We discarded our sample data from the region of Dourados, South Mato Grosso, as long as there is no ethanol price series for this state, and the two corn-ethanol distilleries started their production after 2021.

For all the regions considered, we also used wholesale soybean cash prices because of the close relationship between soybeans and corn production dynamics in these areas. In addition, the use of soybean price returns is important for separating the real effects between the grain markets and ethanol/grain market dynamics.

The returns of commodities prices and exchange rate (r_t) were used for estimations according to expression 1 below.

$$r_t = \ln\left(\frac{P_t}{P_{t-1}}\right) \times 100 \qquad (05)$$

where P_t is the current price collected in the followed data, and P_{t-1} is the price in the previous day than the collected data.

RESULTS

Average connectedness

The average connectedness between market price returns and their volatilities in each market is presented in Tables 1–5, considering the periods before (January 2014 to June 2019) and after (July 2019 to April 2024) the increase in corn ethanol production in Brazil. First, Table 1 shows the average connectedness between regional ethanol markets in Brazil. The results reveal a significant increase in ethanol market connectedness in the second scenario.

Table 1 – Average of the connectivity – Ethanol and sugar markets, Brazil

	Sample I					Sample II				
	EthGO	EthMT	EthSP	SugSP	FROM	EthGO	EthMT	EthSP	SugSP	FROM
EthGO	50.90	5.47	41.21	2.41	49.10	43.28	19.36	36.20	1.16	56.72
EthMT	14.94	63.15	17.63	4.28	36.85	26.74	38.74	32.57	1.95	61.26
EthSP	31.33	5.24	60.29	3.15	39.71	32.98	20.16	44.91	1.95	55.09
SugSP	5.10	4.00	8.60	82.30	17.70	3.90	4.19	6.10	85.81	14.19
TO	51.38	14.71	67.44	9.84	143.36	63.62	43.71	74.88	5.06	187.26
Inc.Own	102.28	77.86	127.72	92.14	cTCI/TCI	106.90	82.44	119.79	90.87	cTCI/TCI
NET	2.28	-22.14	27.72	-7.86	47.79/35.84	6.90	-17.56	19.79	-9.13	62.42/46.82
NPT	2.00	0.00	3.00	1.00		2.00	1.00	3.00	0.00	

Note: Sample I: Jan/2014 - Jun/2019; Sample II: Jul/2019 - Apr/2024; EthGO, EthMT, EthSP and SugSP refer to Ethanol in Goiás, Mato Grosso and Sao Paulo, respectively; SugSP is sugar in Sao Paulo.

After the increase in corn ethanol production in the Brazilian Center-West region, volatility transmission seems to increase in all markets. The Sao Paulo ethanol market is the largest net transmitter, but this leadership was reduced in the second sample period (27.72% to 19.79%). Goiás increased the level of transmission in the second period (from 2.28% to 6.90%), and Mato Grosso remained a net volatility receiver (-22.14% to -17.56%). However, this market showed significant integration with Goiás and Sao Paulo ethanol markets in the second period. Sugar prices do not appear to have a significant effect on other markets. These findings shed light on a new dynamic in the ethanol prices interconnectedness in Brazil, pointing to a recent importance of regional markets in the Center-West.

By analyzing each regional market (Tables 2 to 5), we note an increase in the market average connectedness in the second period compared to the first period. Sorriso and Rondonópolis exhibited the highest increasing ratio, followed by Triangulo Mineiro and Rio Verde. This evidence suggests that changes in market dynamics were stronger in the state of Mato Grosso than in Goiás.

Table 2 – Average of the connectivity – Ethanol, Corn and Soybean, Rio Verde

	Sample I					Sample II			
	CornRV	SoyRV	EthGO	FROM		CornRV	SoyRV	EthGO	FROM
CornRV	90.90	5.42	3.68	9.10	CornRV	86.65	12.36	0.99	13.35
SoyRV	5.03	93.11	1.86	6.89	SoyRV	10.64	88.71	0.65	11.29
EthGO	2.87	0.49	96.64	3.36	EthGO	0.75	0.63	98.62	1.38
TO	7.90	5.91	5.53	19.35	TO	11.39	12.99	1.63	26.02
Inc.Own	98.80	99.02	102.18	cTCI/TCI	Inc.Own	98.05	101.70	100.25	cTCI/TCI
NET	-1.20	-0.98	2.18	9.67/6.45	NET	-1.95	1.70	0.25	13.01/8.67
NPT	0.00	1.00	2.00		NPT	0.00	1.00	2.00	

Note: Sample I: Jan/2014 - Jun/2019; Sample II: Jul/2019 - Apr/2024; CornRV and SoyRV refer to corn and soybeans in Rio Verde region, respectively; EthGO is ethanol in Goiás.

Table 3 – Average of the connectivity – Ethanol, Corn and Soybean, Triangulo Mineiro

	Sample I					Sample II			
	CornTR	SoyTR	EthGO	FROM		CornTR	SoyTR	EthGO	FROM
CornTR	91.92	5.69	2.39	8.08	CornTR	80.56	18.01	1.43	19.44
SoyTR	4.81	94.12	1.07	5.88	SoyTR	13.14	86.27	0.60	13.73
EthGO	5.06	0.59	94.36	5.64	EthGO	0.90	0.45	98.65	1.35
TO	9.87	6.27	3.46	19.60	TO	14.04	18.46	2.02	34.52
Inc.Own	101.79	100.39	97.82	cTCI/TCI	Inc.Own	94.60	104.73	100.67	cTCI/TCI
NET	1.79	0.39	-2.18	9.80/6.53	NET	-5.40	4.73	0.67	17.26/11.51
NPT	1.00	1.00	1.00		NPT	0.00	1.00	2.00	

Note: Sample I: Jan/2014 - Jun/2019; Sample II: Jul/2019 - Apr/2024; CornTR and SoyTR refer to corn and soybeans in Triangulo Mineiro region, respectively; EthGO is ethanol in Goiás.

Table 4 – Average of the connectivity – Ethanol, Corn and Soybean, Sorriso

	Sample I					Sample II			
	CornSR	SoySR	EthMT	FROM		CornSR	SoySR	EthMT	FROM
CornSR	95.17	2.63	2.20	4.83	CornSR	84.95	13.54	1.51	15.05
SoySR	2.31	96.52	1.18	3.48	SoySR	12.45	86.98	0.56	13.02
EthMT	2.37	1.05	96.58	3.42	EthMT	1.51	0.91	97.58	2.42
TO	4.68	3.68	3.38	11.74	TO	13.96	14.45	2.08	30.49
Inc.Own	99.85	100.19	99.95	cTCI/TCI	Inc.Own	98.91	101.44	99.66	cTCI/TCI
NET	-0.15	0.19	-0.05	5.87/3.91	NET	-1.09	1.44	-0.34	15.25/10.16
NPT	1.00	1.00	1.00		NPT	0.00	2.00	1.00	

Note: Sample I: Jan/2014 - Jun/2019; Sample II: Jul/2019 - Apr/2024; CornSR and SoySR refer to corn and soybeans in Sorriso region, respectively; EthMT is ethanol in Mato Grosso.

Table 5 – Average of the connectivity – Ethanol, Corn and Soybean, Rondonópolis

	Sample I					Sample II			
	CornRN	SoyRN	EthMT	FROM		CornRN	SoyRN	EthMT	FROM
CornRN	95.51	3.64	0.85	4.49	CornRN	85.66	10.58	3.75	14.34
SoyRN	2.78	96.05	1.17	3.95	SoyRN	6.59	92.70	0.71	7.30
EthMT	1.54	2.35	96.12	3.88	EthMT	2.67	1.04	96.29	3.71
TO	4.32	5.99	2.02	12.32	TO	9.26	11.62	4.46	25.35
Inc.Own	99.82	102.04	98.14	cTCI/TCI	Inc.Own	94.93	104.32	100.75	cTCI/TCI
NET	-0.18	2.04	-1.86	6.16/4.11	NET	-5.07	4.32	0.75	12.67/8.45
NPT	1.00	2.00	0.00		NPT	0.00	2.00	1.00	

Note: Sample I: Jan/2014 - Jun/2019; Sample II: Jul/2019 - Apr/2024; CornSR and SoySR refer to corn and soybeans in Sorriso region, respectively; EthMT is ethanol in Mato Grosso.

However, most of this increase was due to the connection between corn and soybean markets. Ethanol did not exhibit significant changes in connection with other markets in Rio Verde, Triangulo Mineiro, and Sorriso. Rondonópolis is the only region with an average increase in ethanol interconnectedness. Corn and soybeans exhibit an increase in their connections in all markets. The variation between these two periods was greater in Sorriso and Triangulo Mineiro. This highlights the importance of considering soybean in this study model, given the close evolution of the corn market, especially after the advancement of the corn winter crop.

Beyond average connectedness, another important observation is the change in volatility transmission. Overall, changes were noted in corn and ethanol price returns. In the first period, corn was a net volatility receiver in all regions except Triangulo Mineiro. In the second period, the commodity was a net receiver in all markets and this level increased significantly. However, soybean increased its level as a volatility transmitter in all markets.

Soybean was a volatility receiver only in Sorriso in the first period, but changed to a volatility transmitter in the second period. Ethanol exhibits ambiguous effects. The biofuel changed from a net volatility receiver to a net volatility transmitter in Rondonópolis and Triangulo Mineiro. In Sorriso, ethanol was maintained as a volatility receiver, and the opposite was noted in Rio Verde as a volatility transmitter in both periods. These movements may briefly explain new and discrete regional price dynamics.

Following the analysis of price return connectedness, Figure 4 shows the interconnectedness network in all regions and for ethanol in Brazil during the two analysis periods. As illustrated in Tables 2–5, the findings point to a strong volatility interconnectedness network between soybean and corn in all regions, where soybean is a volatility transmitter and corn is a volatility receiver. In these regions, the regional interconnectedness network for ethanol is weak. However, the separated analysis only between ethanol (and sugar) markets in Brazil indicates an increase in the interconnectedness network, especially in Mato Grosso and Goias, as also indicated in Table 1. However, it is necessary to expand the analysis to include the dynamic connectedness of price returns over time. Figure 4 shows the interconnectedness network for all markets evaluated over the entire period.

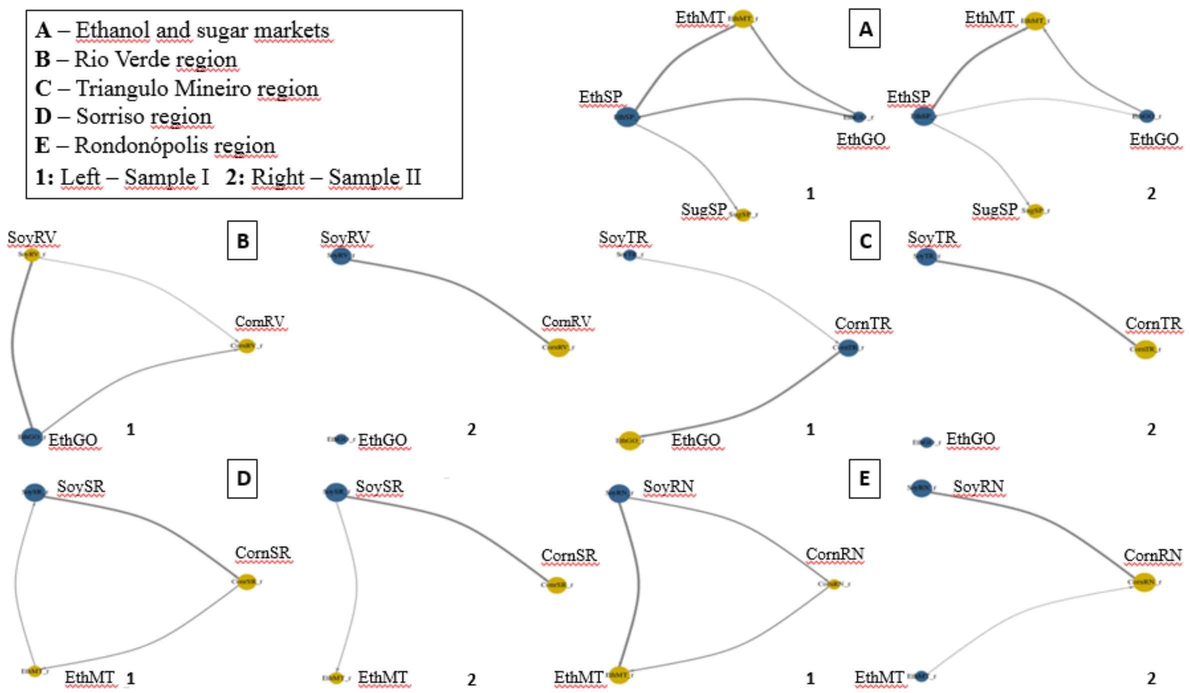

Figure 4 – Return connectedness network among commodities in all regions and periods

Panel A of Figure 5 illustrates the dynamic connectedness between the ethanol markets in Sao Paulo, Goiás, and Mato Grosso. We noted an increase in volatility between regional production areas from late 2018 to 2024. Dynamic connectedness remained at the highest levels since 2020, and peaks were observed between the periods of 2021-2024. This time window is in line with the increase in corn-based ethanol production in the Center-West, and the results might explain the increasing relative linkages between this region and Sao Paulo, a major producer of biofuels in Brazil. Another observation is that the increase in dynamic connectedness between late 2015 and mid-2016, which can be explained by the end of federal intervention in gasoline prices in Brazil. The end of this policy (implemented from to 2011-2015) allowed ethanol prices to flow into a free market and increase market volatility (Drabik *et al*., 2015; Palazzi *et al*., 2022; Janda *et al*., 2022; Quintino *et al*., 2022).

The panel B of Figure 5 shows the Rio Verde region, where the connectedness exhibited an increasing after mid-2020 to late 2023. Although this period is linked to the boom of corn-base ethanol in Brazil, it seems that dynamic connectedness was affected mostly by the covid-19 pandemic, when commodity prices exhibited a fast and abnormal increase. As Figure 5 shows, in the regions of Triangulo Mineiro (panel C), Sorriso (panel D), and Rondonópolis (panel E), we observed a similar increase in dynamic connectedness after 2020. However, in contrast to Rio Verde, the new volatility pattern seems to be higher than in the previous period of the sample. In addition, in Rondonópolis, the highest peak occurred after 2023, suggesting that other factors may affect local price dynamics.

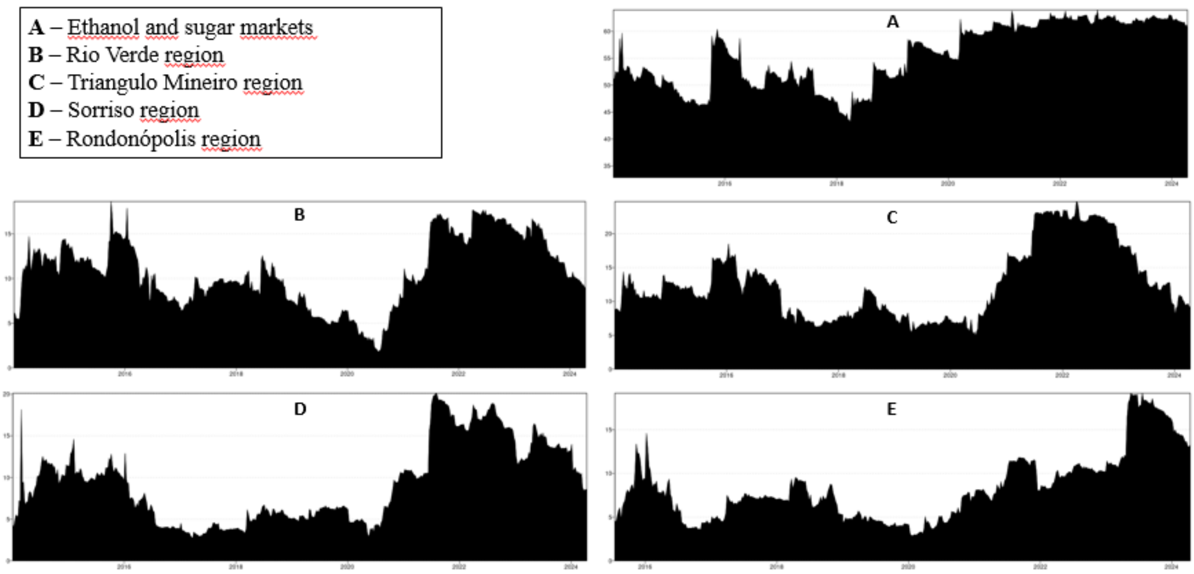

Figure 5 – Dynamic connectedness for all markets – full sample period

Figures 6–10 show the net pairwise directional connectedness between commodities in each regional market. Considering the dynamics between the regional ethanol markets and sugar, we observed that ethanol in Sao Paulo is a net transmitter in all markets, including sugar (Figure 5). The transmission from Sao Paulo to Mato Grosso increased during this period, especially after mid-2018, indicating that the increase in Mato Grosso production led to a strong linkage with other markets. The dynamics between Sao Paulo and Goiás demonstrated a significant rise from to 2016-2019, and then a moderate increase after 2021. The connection between ethanol markets in the Center-West shows that Goiás is a net transmitter of volatility to Mato Grosso, and peaks were observed in 2016, and from to 2019-2021. Sugar seems to be moderated to weakly related to the Sao Paulo and Goiás markets, which is explained by sugarcane production in both states.

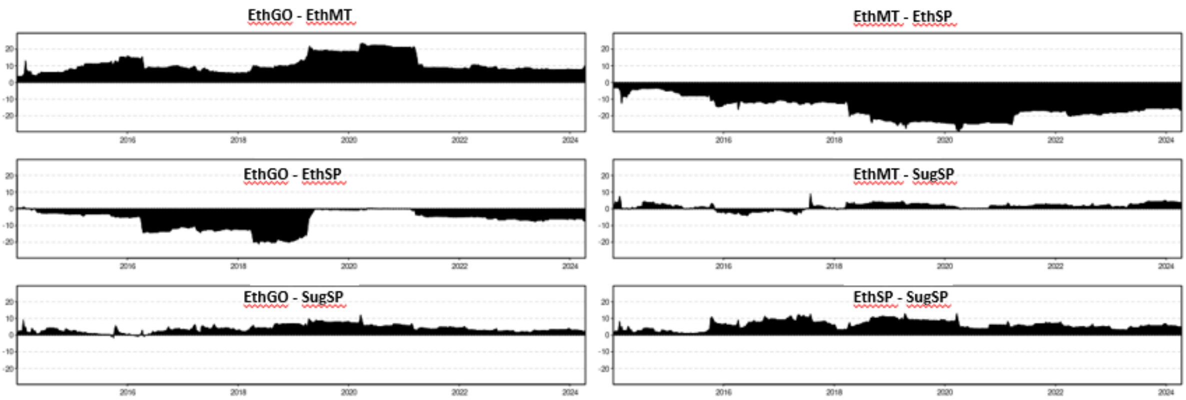

Figure 6 – Net total dynamic directional connecteness for ethanol and sugar markets – full period

The assessment of the net pairwise directional connectedness in regional corn markets shows different results. First, in Rio Verde (Figure 7), the connection between corn and ethanol was strong between 2014-2016, the period before the expansion of corn-based ethanol production. A variation in the volatility direction was also observed during this period, and the most significant was the transmission from ethanol to corn. The direction connectedness is mostly significant between corn and soybean, where corn became a net volatility receiver after 2017, suggesting that corn prices in this area follow the dynamics of soybean prices.

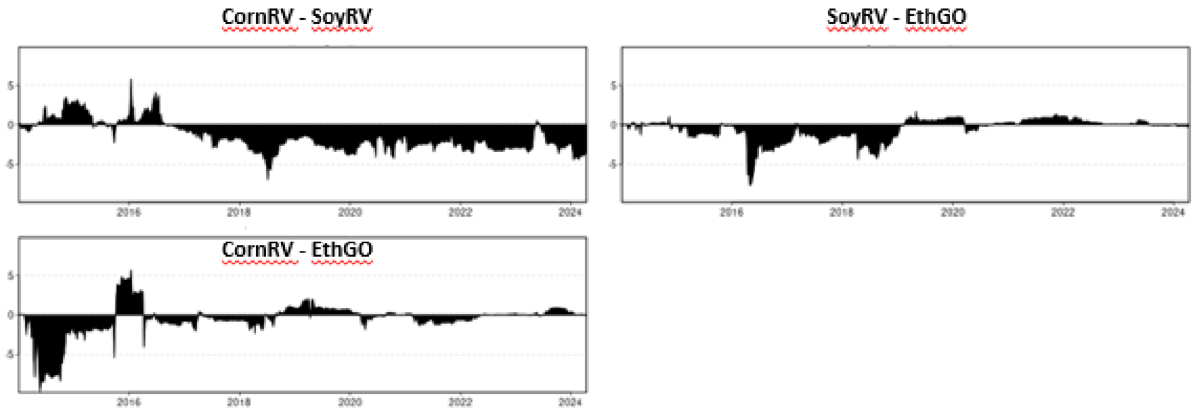

Figure 7 – Net total dynamic directional connecteness for Rio Verde region – full period

In Triangulo Mineiro (Figure 8), the closest region to Rio Verde, the net parwise directional connectedness showed that the connection between corn and ethanol was larger from 2014 to 2019, when corn was a net volatility transmitter. After this period, corn became a net receiver. The linkages between corn and soybeans indicate strong volatility from 2020 to 2024, and corn is a net receiver. This finding is different from that of Rio Verde (in this period) and suggests a relationship with the volatilities in commodity markets after the Covid-19 pandemic.

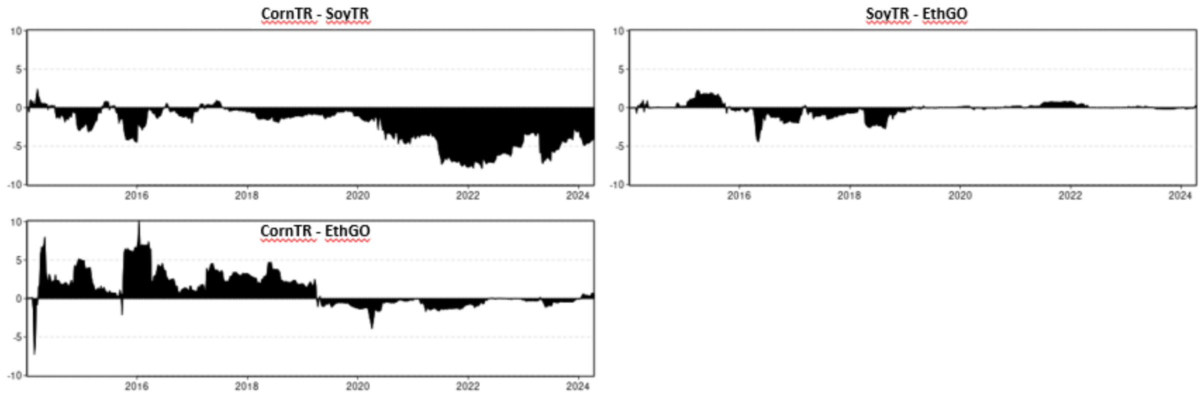

Figure 8 – Net total dynamic directional connecteness for Triangulo Mineiro region – full period

In Mato Grosso, the connections between corn and ethanol are more evident. In Sorriso area (Figure 9), corn and ethanol exhibited greater dynamic connectivity than that between corn and soybean. The linkages between corn and ethanol changed in 2018, when corn became a net volatility transmitter. Transmission maintained a similar pattern, with the exception of 2021. These results are in line with the increase in corn-based ethanol in the region, and the reduction in the connection in 2021 might be explained by abnormal volatilities in commodity markets at the beginning of the Covid-19 pandemic. The relationship between corn and soybean shows that, in most parts of the period, soybeans transmit volatility to corn, especially after 2021.

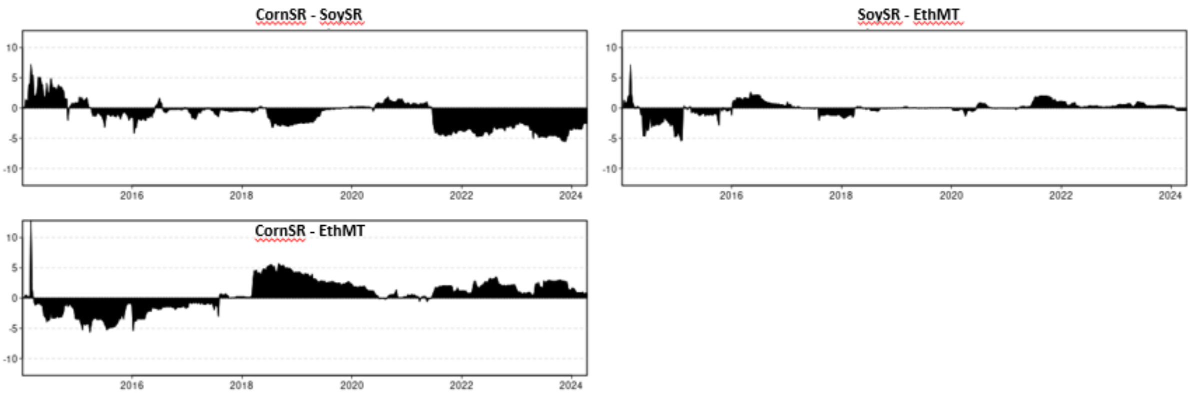

Figure 9 – Net total dynamic directional connecteness for Sorriso region – full period

In Rondonópolis (Figure 10), the connection between corn and soybeans was greater than that in Sorriso, and corn was a net volatility receiver (as observed in all other regions), with the highest peaks after 2020 and the Covid-19 outbreak. The dynamic connectedness between corn and ethanol shows an increasing between 2019-2019, and from 2023-2024. During these periods, corn was a net volatility transmitter of ethanol. These results were partially related to those observed in Sorriso. However, there are only two corn-based ethanol distilleries in the Rondonópolis region, and mills were established later (2020 and 2021). In contrast, the Sorriso region has six corn-based ethanol plants, some of which were established in 2017-2018. This explains why the integration of corn and ethanol prices is greater in this region.

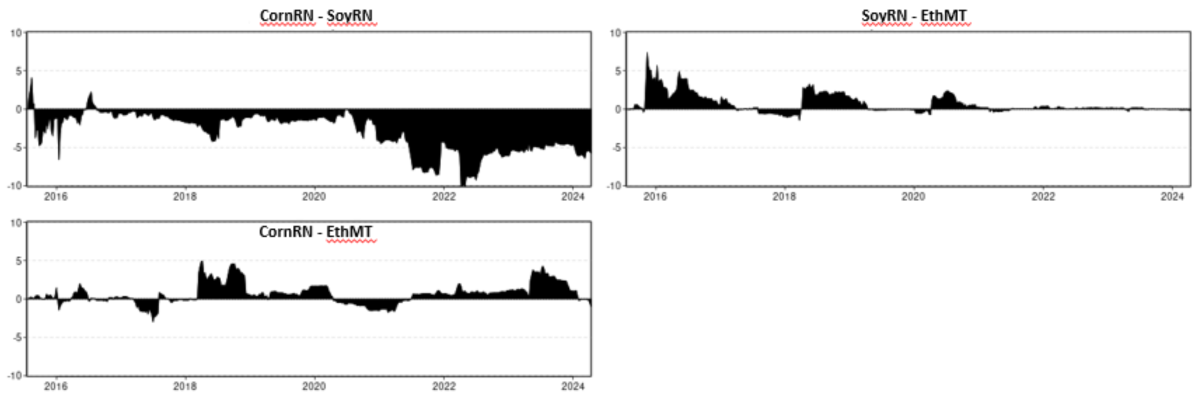

Figure 10 – Net total dynamic directional connecteness for Rondonópolis region – full period

CONCLUSION

This study proposed to examine the possible changes in the regional dynamic connectedness of the price returns of ethanol and corn after the recent expansion of corn-based ethanol in Brazil. We analyzed four regional markets in the Brazilian Center-West, where corn-based ethanol production is located. These locations are in the regions of Rio Verde, Triangulo Mineiro, Sorriso, and Rondonópolis. Soybean price returns were also considered because of the close relationship between corn and soybean production in this geographical area. Additionally, we also examined the dynamic connectedness of ethanol price returns in Center-West Brazil (states of Goiás and Mato Grosso) and the state of Sao Paulo, where sugarcane-based ethanol is largely disseminated and drives biofuel prices in the country.

For this analysis, we employed a TVP-VAR, considering the specifications proposed by Antonakakis *et al*. (2020), which allows the examination of volatility spillovers and dynamic connectedness among the markets. The analysis period is from January 2014 to April 2024. The impacts were examined in two different periods, separating the period in which corn-base ethanol production was irrelevant from the period in which production increased. Therefore, two samples were considered in this study. The first was from January 2014 to June 2019 and the second was from June 2019 to April 2024.

First, our findings indicate that the dynamic connectedness between ethanol markets in Brazil changed after 2019, when volatility transmission increased among Sao Paulo, Goiás, and Mato Grosso ethanol price returns. The newly established connections were greater for the state of Mato Grosso, with an increase in net directional connectedness, highlighting the state as a volatility receiver from Sao Paulo and Goiás ethanol markets. These findings suggest that the establishment of corn-based ethanol production in Mato Grosso led the state to become connected with the major ethanol producer markets, as Sao Paulo. On the other hand, sugar exhibited weak connection with ethanol prices in Sao Paulo and did not integrate with ethanol production in the Center-West, differently from what previous studies observed (Balcombe & Rapsomanikis; Bentivoglio et al., 2016; Capitani, 2018). This finding may confirm that changes have occurred over these markets.

Furthermore, the analysis of the regional markets in Rio Verde, Triangulo Mineiro, Sorriso, and Rondonópolis does not show a significant change in the dynamic connectedness between corn and ethanol price returns, especially in the regional markets linked to the Goiás ethanol market. However, in Sorriso and Rondonópolis (Mato Grosso), we observe an intensification of the dynamic directional connectedness between corn and ethanol price returns after 2018. These findings are in line with the observation of an increase in the dynamic connectedness between ethanol price returns in Mato Grosso, where the local market is a volatility receiver from Goiás and Sao Paulo. This might indicate that the beginning of corn-based ethanol production in Mato Grosso has influencing the regional connection between ethanol and corn prices in a moderate level.

Additionally, the findings indicate a strong connection between corn and soybean price returns in the regional spots of the Brazilian Center-West region. As expected, this connection is a consequence of an increase of 120% and 86% in the Center-West corn and soybean production, respectively, considering the period in this study analysis (CONAB, 2024). As mentioned, the recent increase in corn winter harvest in the Center-West improved the regional production dynamics between both commodities.

Beyond these results, it is important to highlight the effects of the Covid-19 pandemic on volatility transmission from mid-2020 to the coming years, as pointed out by several studies (e. g., Dmytrów *et al*., 2021; Mishra *et al*., 2023; Pallazzi *et al*., 2023). Corn and soybean prices in Brazil increased by 80% and 100%, respectively, in an interval between 9-15 months after the Covid-19 outbreak. At this interval, the maximum increase in ethanol was approximately 56% (CEPEA, 2024). The period of this abnormal fluctuation coincided with the period of increase in corn-based ethanol production in Brazil, and our analysis could be affected.

In this sense, the study analysis may be improved by including new data series in the forthcoming years. Another limitation is the use of weekly ethanol data in the Center-West, which reduces the time series used in the subsample intervals. A possible approach is to use the daily ethanol prices of Sao Paulo state. This would also lead to the inclusion of new regional markets around the Center-West, where the series begin after 2017/18. In addition, an adjustment can be made by excluding the 2020/21 data series, which would allow for the estimation of two different sample periods with sufficient observations. Finally, an extension of the analysis can be improved to examine whether local changes in ethanol production in Brazil can influence the volatility transmission in the international market, especially considering the connections between the USA and Brazil.

Overall, although the study brings new elements to the literature, as it is the first study to propose an analysis of volatility transmission in the Brazilian biofuel regional markets after the expansion of corn-based ethanol production in the country. Our findings shed light on whether a gradual change in biofuel production feedstock can have consequences for local commodities prices. The results can support new research focus in commodity price analysis, the connection between biofuels and agricultural production, and biofuel market integration.

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