Impactos Energéticos, Ambientais e Socioeconômicos das Usinas Dedicadas ao Etanol de Milho

Energy, Environmental, and Socioeconomic Impacts of Dedicated Corn Ethanol Plants

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SOBER GT12. Impactos socioambientais das novas tecnologias no agronegócio

Resumo: Este artigo avalia os impactos energéticos, ambientais e socioeconômicos da adoção de usinas full de etanol de milho no Centro-Oeste brasileiro. Utilizando dados em painel para microrregiões no período de 2015 a 2023, aplica-se uma abordagem de Diferenças-em-Diferenças duplamente robusta para estimar efeitos causais sobre o consumo relativo de etanol, as emissões de gases de efeito estufa e o emprego. Os resultados indicam que a implementação dessas usinas aumenta o consumo relativo de etanol, sugerindo expansão da competitividade do biocombustível em regiões antes menos atendidas. Por outro lado, as emissões aumentam, indicando que efeitos do processo produtivo podem superar ganhos da substituição de combustíveis. Em termos socioeconômicos, há aumento do emprego total, com efeitos positivos nos setores agrícola, industrial e, principalmente, de serviços, que se intensificam ao longo do tempo.
Palavras-chave: Bioenergia. Etanol de milho. Impactos socioeconômicos. Impactos ambientais

Abstract: This article evaluates the energy, environmental, and socioeconomic impacts of adopting full corn ethanol plants in Brazil's Midwest. Using panel data for microregions from 2015 to 2023, the study applies a doubly robust Difference-in-Differences approach to estimate causal effects on relative ethanol consumption, greenhouse gas emissions, and employment. The results indicate that the implementation of full plants increases relative ethanol consumption, suggesting an expansion of biofuel competitiveness in previously underserved regions. At the same time, greenhouse gas emissions rise on average, indicating that production-related effects may outweigh gains from fuel substitution. In socioeconomic terms, total employment increases, with positive effects observed across agricultural, industrial, and especially service sectors. Dynamic estimates show that these effects are not immediate but intensify over time, reflecting the gradual expansion of production capacity and regional economic linkages.
Keywords: Bioenergy. Corn ethanol. Socioeconomic impacts. Environmental impacts.

1. Introduction

From the Kyoto Protocol (COP3, 1997) to the recent conference in Dubai (COP28, 2023), nations have committed to reducing CO_2 emissions in order to mitigate the impacts of climate change. The two most widely discussed strategies for decarbonizing developing economies are the reduction of fossil fuel consumption and the control of deforestation. In the transport sector, Brazil has implemented two main biofuel initiatives: ethanol and biodiesel. Ethanol production in the country dates back to the 1970s oil crisis, when the Pro-Alcohol Program was introduced to reduce dependence on gasoline by partially replacing it with ethanol

(Wilkinson and Herrera, 2010). As a result, the development of the ethanol industry has been closely associated with sugarcane, which remains the main feedstock used in the country (Goldemberg et al., 2008).

Despite the predominance of sugarcane, ethanol production from corn began to expand from the 2010s onward, introducing an additional feedstock into the sector. This process initially occurred through the adoption of flex plants, which process both sugarcane and corn, allowing firms to adjust feedstock use over the production cycle. Subsequently, dedicated units known as full plants, designed to process corn exclusively, were introduced (Gurgel et al., 2024).

The emergence of full plants is associated with a set of structural factors. On the supply side, the expansion of second-crop corn production in Brazil's Midwest increased the availability of the main input, often at relatively lower prices due to logistical constraints and distance from export markets (Moreira et al., 2020; Silva and Castañeda-Ayarza, 2021). On the demand side, the spatial concentration of sugarcane ethanol production limited the competitiveness of ethanol in several regions, indicating the existence of potential markets not fully served (ANP, 2024). In addition, the production of co-products, such as DDGS, contributes to the economic viability of these plants by strengthening linkages with related sectors (Eckert et al., 2018; Gurgel et al., 2024).

The expansion of corn ethanol production through full plants may generate effects across multiple dimensions. In terms of energy, the increased local supply of ethanol may contribute to higher relative consumption, particularly in regions where the fuel was previously less competitive. From an environmental perspective, the net effect on greenhouse gas emissions is ambiguous, as potential reductions from fuel substitution may be offset by increases associated with agricultural production, industrial processing, and logistics (De Oliveira and Coelho, 2017; Wang et al., 2012). In socioeconomic terms, the installation of full plants may affect employment through increased demand for agricultural inputs, industrial activities, and services related to transportation and distribution (Moreira et al., 2020).

In this context, this article aims to evaluate the impacts of the adoption of full corn ethanol plants on relative ethanol consumption, greenhouse gas emissions, and Employment (both total and by sector) in microregions of Brazil's Midwest. To this end, the study employs panel data for the period from 2015 to 2023 and applies a doubly robust Difference-in-

Differences approach, allowing for the identification of causal effects associated with the implementation of this production model.

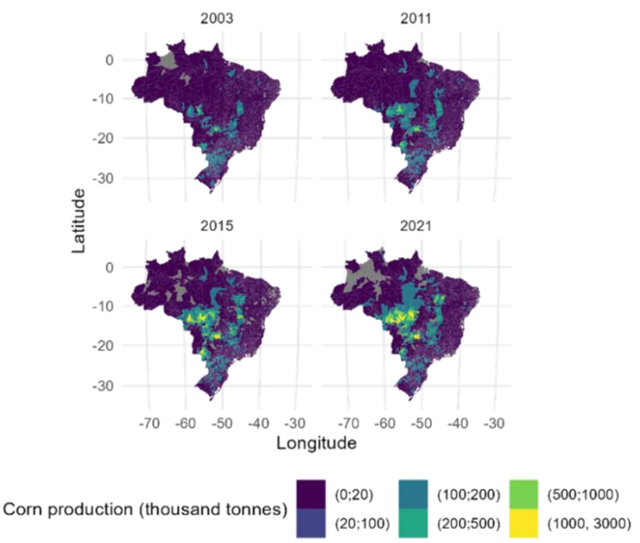
2. Literature Review

2.1 Theoretical and empirical aspects

The growth of the corn ethanol sector began with the adoption of the flex production model by sugarcane ethanol mills and reached an important milestone in 2017 with the emergence of a new production structure: full mills, which process grain exclusively for biofuel production (Gurgel et al., 2024). While the diversification of raw materials in the flex model is a competitive strategy adopted by companies in the sugarcane ethanol sector, the installation of new plants dedicated to corn ethanol represents the exploitation of a scenario of favorable competitive conditions for the birth of a new sector, including production factors, demand conditions, and conditions in related sectors (Nogueira Junior, 2022).

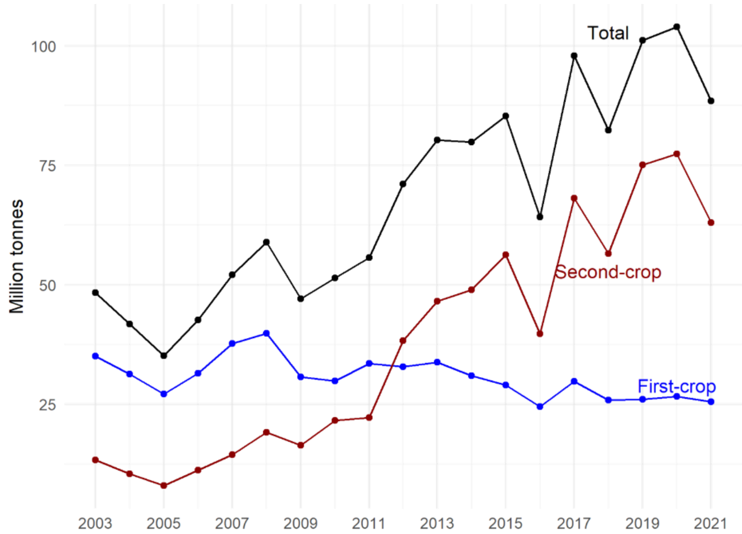
Regarding production factor conditions, it should be noted that corn production and productivity have expanded significantly over the last two decades, from 57 million tons grown on 13 million hectares in the 2010/2011 harvest to 100 million tons grown on 17 million hectares in the 2018/19 harvest (Conab, 2023b). The growth in corn production and productivity in the country is mainly attributed to two closely interrelated factors: the increased importance of the Midwest region in grain production and the expansion of the second-crop corn (Souza et al., 2018; Colussi et al., 2023; Bigolin and Talamini, 2024; Volsi et al., 2022).

Figure 1: Corn production by city



Data from Sidra-IBGE. Corn production, measured in thousand tones, by city in Brazil.

Figure 2: Corn production in Brazil



Data from IBGE-Sidra. Corn production is measured in millions of tones.

Figure 1 illustrates the spatial evolution of corn production in Brazil over the period from 2003 to 2021, showing significant growth in both volume and geographic concentration. The Midwest region has consolidated its position as the main production hub, with the states of Mato Grosso, Mato Grosso do Sul, and Goiás accounting for a growing share of national production. According to Neves et al. (2021), corn is a highly versatile crop that can be grown in up to three different seasons in Brazil, depending on the specific soil and climate conditions of each region. In the summer, the crop is classified as first-crop corn; when planting occurs from January onwards and harvesting takes place in winter, it is called second-crop corn; and when sowing occurs between May and June, it is known as third-crop corn.

In the central region of the country, which concentrates the main producing states, a production system based on two central commodities has been consolidated in recent years, as noted by Bigolin and Talamini (2024): soybeans as the first crop and corn as the second crop. As illustrated in Figure 2, the significant growth in national corn production can be attributed mainly to the expansion of second crop production, which has become the main driver of the increase in grain supply in the country (Neves et al., 2021).

The technical and financial viability of growing second-crop corn in the Midwest of the country, in rotation with soybeans, has three main consequences. First, there is reduced competition for land between the two crops, since the second-crop production system allows corn to be grown in a complementary manner, without the need for significant expansion of agricultural land (Garofalo et al., 2025; Pinheiro et al., 2021). Second, the adoption of integrated production systems reduces the demand for additional fertilization and provides relevant agronomic benefits, such as pest control, soil conservation, and nutrient recycling (Pinheiro et al., 2021).

Finally, the growth in second-crop corn production in the Midwest states, combined with the logistical inefficiency of domestic grain transportation in Brazil and the distance between the producing regions and the main export ports, has favored access to corn at relatively lower prices in states such as Mato Grosso, Mato Grosso do Sul, and Goiás (Moreira et al., 2020; Silva and Castañeda-Ayarza, 2021). This context creates favorable economic conditions for the establishment of industries that are intensive in corn as an input, including corn ethanol plants.

This scenario represents a significant competitive advantage in terms of production factors. As highlighted by Neves et al. (2021), the main costs of corn ethanol production are associated with raw material. In this sense, the high local availability of second-crop corn at relatively lower prices, resulting from production expansion in the Midwest and logistical limitations on export distribution, significantly reduces the acquisition costs of the main input in the process.

In terms of demand factors, there is a potential market for biofuels that has not yet been explored in the country. With regard to competitiveness between hydrated ethanol and gasoline, data from the Fuel Resale and Distribution Price Survey conducted by the National Agency of Petroleum, Natural Gas and Biofuels (ANP, 2024) show that, between 2013 and 2023, ethanol was considered competitive (priced at up to 70% of the price of gasoline) in only 26% of the total sample (the sample being composed of cities on an annual basis).

The ANP (2024) also indicates that, between 2013 and 2023, ethanol was considered competitive in 63% of the municipalities in the sample in the state of São Paulo and in 43% of the municipalities in the sample in Minas Gerais, the two largest sugarcane producers in the country. In contrast, in the states of northern Brazil, ethanol was not competitive in any municipality, regardless of the period analyzed.

These results highlight a historical trend whereby municipalities located near sugarcane mills, the main raw material for ethanol in Brazil, are more likely to enjoy more favorable biofuel prices. This pattern reflects the location strategy of these mills, which are traditionally located near sugarcane growing areas, so that the competitiveness of ethanol in the country remains largely restricted to regions where this crop is predominant.

In this context, the significant increase in corn production in Brazil, combined with the spread of technologies that use this raw material to produce biofuels, introduces a new element into the competitive dynamics of Brazilian ethanol: proximity to large corn-producing regions. One of the main advantages of this new production chain lies in the possibility of supplying ethanol to regions where, historically, its price was not competitive with gasoline, revealing the existence of a potential demand that has not yet been fully met.

Finally, regarding related and supporting sectors, it should be noted that ethanol production from corn generates co-products with significant economic potential, in particular Distillers Dried Grains with Solubles (DDGS), widely used in animal feed, and vegetable oil (Gurgel et al., 2024; Eckert et al., 2018). The generation of these co-products adds greater complexity to the economic structure of the mills, especially in the context of high corn price volatility. In this scenario, strategies such as price hedging, advance grain purchases, and storage become important, but the use of complementary revenues from co-products plays a central role in mitigating risks and stabilizing profit margins.

In this context, as argued by Nogueira Junior (2022), the combination of structural factors, notably the high availability of the main input at relatively low costs, the spatial concentration of ethanol supply that reveals the existence of regional markets not yet fully served, and the economic exploitation of related sectors through the generation of co-products, created favorable conditions for attracting investment and consolidating corn ethanol full plants in the Brazilian Midwest. These elements, acting in a complementary manner, not only sustain the economic viability of this production model, but also explain the emergence and expansion of a new segment within the biofuel chain in the country.

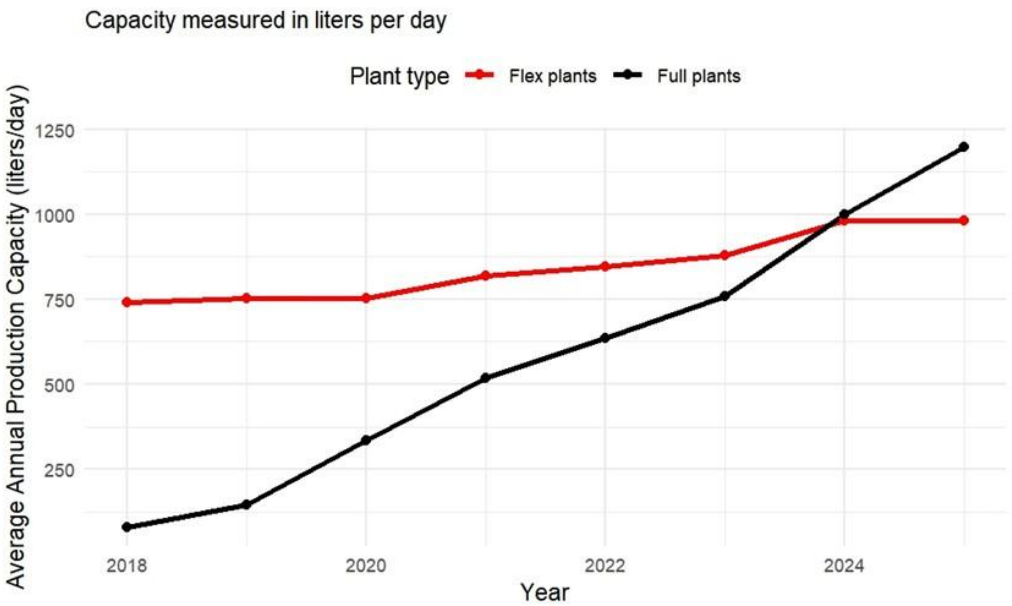
2.1 Effects of Full Distilleries

The adoption of the full production model can generate significant effects on biofuel consumption, as well as environmental and socioeconomic impacts (Gurgel et al., 2024). In the case of dedicated (full) plants, they are located in areas with high corn production, mainly in the states of the Midwest region (Eckert et al., 2018), where the expansion of the second corn crop has led to significant growth in both production and grain productivity. While ethanol production from sugarcane is geographically restricted to specific regions due to transportation costs and product characteristics, the introduction of this new technology enables biofuel production in regions where it was previously of smaller relevance.

This expansion increases consumers' access to ethanol at competitive prices. In this context, while the energy impact of adopting the flex production model is to increase relative ethanol consumption by ensuring its competitiveness throughout the year, the energy impact of adopting full plants is to increase the competitiveness of biofuel in regions where it was previously less relevant. In addition, the significant expansion of the production capacity of full plants in a short period of time stands out, which can considerably impact the competitiveness of ethanol in the regions where these plants are located. Figure 3 shows the evolution of the average production capacity of flex and full plants in Brazil between 2018 and 2025, based on data from the National Agency of Petroleum, Natural Gas, and Biofuels.

From an environmental perspective, a positive local environmental impact occurs when the emissions avoided by using cleaner energy sources in transportation exceed the additional emissions generated during the stages of raw material production, processing, and biofuel distribution (De Oliveira and Coelho, 2017). For full plants, the increase in emissions associated with installing a new plant may be due to several factors. These include the expansion of grain cultivation, the development of related sectors such as livestock (driven by the increased supply of co-products) and the intensification of transportation demands for both inputs and final products. Most importantly, it may also reflect the additional energy requirements necessary to maintain the production process.

Figure 3: Evolution of ethanol production capacity on flex and full mills



Data from Sidra-IBGE. Sugarcane production, measured in million tons, by city in Brazil.

While plants that exclusively produce ethanol from sugarcane, as well as flex plants, rely on biomass (bagasse) generated during the production process to supply energy, full plants depend on external energy sources. In the United States, corn ethanol plants mainly rely on fossil fuels for energy generation, while in Brazil these plants typically use eucalyptus biomass (Moreira et al., 2020). Although the Brazilian production process generally results in lower emissions, the expansion of eucalyptus cultivation may lead to an increase in cultivated land area and potentially contribute to deforestation.

In North American corn ethanol production, the largest contributor to life-cycle greenhouse gas (GHG) emissions is the cogeneration of energy from fossil fuels (Wang et al., 2012). In contrast, Brazilian full corn ethanol plants typically use biomass, mainly eucalyptus, for energy generation (Neves et al., 2021), thereby reducing reliance on fossil fuels and contributing to lower overall emissions. However, unlike flex plants, the biomass used for energy generation in full plants is not readily available as a by-product of the production process and must therefore be sourced externally.

Moreover, the expansion of local production capacity associated with full plants is considerably larger than that observed in the adoption of flex model. This expansion has implications for the demand for inputs and the distribution of outputs, which may significantly affect total emissions. Consequently, it is necessary to investigate the environmental implications, particularly in terms of greenhouse gas emissions, associated with the implementation of full corn ethanol plants.

Regarding the effects on employment, it should be noted that the installation of a dedicated (full) plant generates substantial demand for agricultural inputs, such as corn and eucalyptus (used for energy cogeneration), and industrial inputs, such as chemical and biological products used in grain processing. The industrial stage of the production process also stimulates job creation in the plants, including skilled labor for the operation, monitoring, and control of the equipment and technologies used. In addition, the intensification of the flow of inputs, products, and co-products tends to boost the logistics and transportation sector in the affected locations. The generation of co-products, in turn, can significantly impact specific sectors, such as livestock, which uses DDGS in animal feed, strengthening regional production chains. (Moreira et al., 2020).

3. Methodology

3.1 Empirical Strategy

This article aims to investigate the energy, environmental, and socioeconomic impacts of adopting corn ethanol technology based on the full model in the Midwest region of Brazil. To this end, panel data from the micro-regions comprising the Midwest region for the period from 2015 to 2023 are used, and a doubly robust Difference-in-Differences approach is employed, as proposed by H.C. and Zhao (2020) and Callaway and Sant'Anna (2021).

The doubly robust model generalizes the canonical Difference-in-Differences (DiD) model, allowing for analysis of multiple periods and staggered treatment, that is, situations in which treatment occurs in different periods for different units. In the context of this study, the treatment considered, the adoption of the full ethanol production model, involves multiple periods and units (micro-regions) that are treated at different points in time. The treatment occurs when a micro-region i receives an ethanol production plant exclusively from corn in period t. Thus, the treatment group consists of micro-regions that have a full plant in operation, while the control group consists of micro-regions that do not have a full plant in operation.

The doubly robust Difference-in-Differences method estimates several parameters of the average treatment effect by group and period. These groups are defined by the time at which a unit is first treated, and each specific group-time average effect parameter, denoted by ATT (g, t), represents the causal effect of the treatment in period t for the group of units initially treated in period g.

$$ATT\ (g,t) = E[Y_{i,t} - Y_{i,g-1} | G_i = g] - E[Y_{i,t} - Y_{i,g-1} | G_i = \infty] \quad (1)$$

The ATT (g, t) is identified by comparing the expected variation in the outcome of treatment group g between $g - 1$ and t with the corresponding variation in a control group composed of units that have never been treated. This prevents comparisons between groups treated in each period and groups that have not yet been treated but will receive treatment later. The ATT (g, t) allows for heterogeneity in the treatment effect between groups (defined by the initial treatment period) and over time.

To identify the ATT (g, t), certain assumptions are required. One key assumption is the limited treatment anticipation hypothesis, which allows treated units to exhibit anticipation effects, provided that the anticipation horizon is explicitly defined. This is feasible because the identification strategy for ATT (g, t) enables the estimation of causal effects even in periods preceding a unit's initial treatment, that is, when $t < g$.

In the context of the treatment analyzed in this study, the adoption of the full model assumes the absence of anticipation effects. It is argued that the investment cycle associated with the implementation of new industrial plants, which includes the construction stage (Silva and Castañeda-Ayarza, 2021), does not exceed, on average, a period of one year, which corresponds to the minimum time unit considered in the database. Thus, any effects resulting from the investment process would not be captured in periods before the actual start of the plant's operation.

In addition to the hypothesis of limited anticipation of treatment, the model proposed by Callaway and Sant'Anna (2021) assumes that, conditional on a set of covariates, the average results of the group treated for the first time in period g and the "not yet treated" group in period $t + \delta$ would have followed parallel trajectories in the absence of treatment. In other words, the hypothesis of parallel trends in the model by Callaway and Sant'Anna (2021) consists of a generalization that assumes that this condition is valid only conditionally on a set of covariates.

The conditional parallel trends assumption is particularly relevant when the distribution of covariates differs between the treatment and control groups, and when these covariates influence the temporal trajectory of the outcomes (Callaway and Sant'Anna, 2021). When analyzing the impacts of adopting corn-based ethanol production technology in the full model, it is essential to consider that micro-regions may have structural characteristics that increase the likelihood of establishing this type of plant. As stated by Nogueira Junior (2022), several factors, particularly those related to the availability of input and the existence of consumer markets for output, have contributed to the establishment of the sector in the region under analysis.

In this context, two key drivers of the adoption of the full model are identified. First, corn production plays an important role, as the activity requires large volumes of this raw material, and transportation costs significantly affect the economic viability of the project. Second, initial ethanol consumption is also relevant, since relatively low levels before the plant's installation may indicate unmet local demand and, therefore, potential for market expansion.

Therefore, the distribution of the variables representing these factors may differ significantly between micro-regions that have full-scale power plants and those that do not. When the trajectory of any variable of interest depends on these covariates, the hypothesis of conditional parallel trends becomes more plausible than the hypothesis of unconditional parallel trends in the traditional differences-in-differences (DiD) model. In the study, there are three main variables of interest: relative ethanol consumption, emissions, and employment.

In the case of relative ethanol consumption, the parallel trends assumption is assumed to be conditional on the initial relative ethanol consumption. In the case of emissions, it is assumed that the parallel trends hypothesis is conditional on initial relative ethanol consumption and corn production, since these factors are strongly associated with the level of productive activity and fossil fuel consumption and, consequently, with emissions generation in the regions. Finally, in the case of employment, both total and by sector, it is assumed that the parallel trends hypothesis is conditional on corn production, given that local income, productive structure, and economic dynamism play a fundamental role in determining the level of regional employment.

The doubly robust difference-in-differences method is a strategy that accommodates potential violations of the two main identification assumptions of the traditional DiD framework. The method allows for the existence of anticipation effects and accepts the validity of the parallel trends hypothesis conditional on the observed covariates. By incorporating these adjustments, the approach increases the robustness of causal inference in contexts where the standard assumptions of the conventional differences-in-differences model may not be fully satisfied (Callaway and Sant'Anna, 2021). Thus, the procedure helps mitigate concerns regarding compliance with the fundamental requirements of the DiD methodology, ensuring more reliable and precise estimates of treatment effects.

As highlighted by Callaway and Sant'Anna (2021), an attractive feature of the group and period specific average treatment effect parameters is that they do not impose direct restrictions on heterogeneity with respect to observed covariates, the period in which units are first treated, or the temporal evolution of treatment effects. Furthermore, the authors demonstrate how to aggregate the average treatment effects by group and period into different summary statistics, facilitating the analysis of specific heterogeneities. This aggregation can be done by exposure time (event study), by group, and by calendar time.

A potential limitation of the method is that the validity of the estimated parameters depends on the assumption of no spillover effects; that is, it is assumed that the treatment applied to one unit does not affect the outcomes of other units. If this assumption is violated, the estimates of the causal effect may be biased, since part of the treatment's impact could spread to the control group.

In the present study, defining micro-regions rather than individual municipalities as treatment units aims precisely to mitigate this problem. The installation of an ethanol plant can generate effects that extend beyond the administrative boundaries of the municipality where it is located, such as impacts on biofuel consumption, employment, income, and emissions in neighboring municipalities. By aggregating municipalities into micro-regions, I seek to internalize these potential spatial effects within the Treatment unit itself, reducing the risk that units classified as controls are indirectly affected by the treatment.

3.2 Data

The data used in this study include annual data for all micro-regions of the Brazilian Midwest for the period from 2015 to 2023. To construct the treatment and control groups, data from the National Agency of Petroleum, Natural Gas and Biofuels (ANP) were used, which periodically updates information regarding petroleum, natural gas, and biofuels sectors.

The treatment group consists of the micro-regions in which at least one full-scale plant operates, producing ethanol exclusively from corn. The control group, on the other hand, consists of micro-regions that do not have a full-scale plant in operation. The information used was extracted from the ANP's Dynamic Panel of Ethanol Producers, which provides tabulated data on the ethanol plants authorized to operate in the country, including their locations and the raw materials used in the production process. Based on this data, 23 ethanol plants that primarily process corn were identified.

Subsequently, a documentary analysis was conducted to identify the year of implementation of each mapped plant. It was found that, among the 23 identified plants, 8 were installed after 2023, while 15 had begun operations by 2023. Among the 15 full plants installed between 2015 and 2023, three were excluded from the sample. The Bioflex plant, located in the municipality of Poconé, was installed in 2019; however, its operating authorization was revoked by the ANP in 2023, which compromised the continuity of its operations during the analysis period.

Likewise, the Cereale plant, located in Dois Córregos, in the state of São Paulo, in addition to being the only plant classified as *full* outside the Center-West region, is characterized in the literature, such as in Neves (2021) and Nogueira Júnior (2022), as a *flex* plant, despite the ANP indicating corn as the sole feedstock used. Given this classification inconsistency, its exclusion was deemed appropriate to preserve the methodological coherence of the sample.

Finally, the Destilla Bioenergia plant, located in Itaúba and commissioned in 2015, exhibited negligible production capacity throughout the entire period analyzed: approximately 5 liters per day, a volume incompatible with industrial-scale commercial operations. Due to its lack of economic relevance and limited potential for regional impact, this unit was also excluded from the sample.

Given the construction of the treatment variable, the treated group consists of the microregions with operating *full* plants, with the initial treatment year defined as the year in which the first installed *full* plant began operations. Of the 52 microregions in the Midwest, 7 belong to the treated group, as shown in Table I below. The remaining 45 microregions compose the control group.

Table I: Treated Units

Microregion	State	Year of Adoption of the Full Model (G)
Alto Teles Pires	MT	2017
Sinop	MT	2018
Sudoeste de Goiás	GO	2019
Alto Paraguai	MT	2021
Primavera do Leste	MT	2021
Dourados	MS	2022
Vale do Rio dos Bois	GO	2023

Elaborated by the authors.

Six outcome variables are analyzed, relating to the energy, environmental, and socioeconomic impacts of the implementation of a *full* plant. The first refers to the relative ethanol consumption in municipality i in year t, constructed to capture the share of hydrous ethanol in total fuel consumption while accounting for differences in energy efficiency between ethanol and gasoline. This variable is defined as follows in Equation (1):

$$Relative\ Ethanol\ Consumption_{it} = \frac{0{,}7\ x\ Hydrous\ Ethanol\ Consumption_{it}}{Gasoline\ Consumption_{it} + 0{,}7\ x\ \ Hydrous\ Ethanol\ Consumption_{it}} \quad (2)$$

Where the subscript i denotes the municipality and the subscript t the reference year. Data on hydrous ethanol and gasoline consumption were obtained from the National Agency of Petroleum, Natural Gas, and Biofuels (ANP). The 0.7 factor reflects ethanol's lower energy efficiency compared to gasoline.

The second variable of interest is greenhouse gas emissions. Emissions data are obtained from the Greenhouse Gas Emissions and Removals Estimation System (SEEG), which provides annual estimates of greenhouse gas emissions in Brazil. The emissions variable used in the present analysis correspond to:

$$Per\ Capita\ Emissions_{it} = \log\left(\frac{CO_2e\ emissions_{it}}{Population_{it}}\right) \quad (3)$$

Where CO_2e emissions denote gross GHG emissions, measured in carbon dioxide equivalent, in municipality i at time t, and Population denotes the corresponding municipal population. The third variable of interest, which measures the socioeconomic impacts of adopting the flex model, is employment. Information related to employment is sourced from the Annual Social Information Report (RAIS). Employment is measured by:

$$Employment_{it} = \log\left(Formal\ Employment\ Ties_{it}\right) \quad (4)$$

Where Formal employment ties correspond to the number of formal employment contracts registered in municipality i in year t. In addition to total employment, the analysis also considers disaggregated measures by major economic sectors, as defined by the Brazilian Institute of Geography and Statistics (IBGE): rural (agriculture and livestock), industry, and services. In these cases, the variable assumes the same functional form, differing only in the sectoral scope of formal employment ties, namely: rural employment, industrial employment, and services employment.

As previously discussed, the parallel trends assumption is taken to hold conditional on covariates that simultaneously affect both the probability of treatment and the temporal trajectory of the outcome variable. In the case of relative ethanol consumption, the covariate included in the model is the initial relative ethanol consumption. For emissions, the covariates included in the model are initial relative ethanol consumption and corn production, whereas for employment, both total and sector-specific, the covariate included is corn production. In this sense, two covariates are defined. Initial relative ethanol consumption is defined as follows:

$$Initial\ Relative\ Ethanol\ Consumption_i = \frac{0{,}7\ x\ Initial\ Hydrous\ Ethanol\ Consumption_i}{Initial\ Gasoline\ Consumption_i + 0{,}7\ x\ \ Initial\ Hydrous\ Ethanol\ Consumption_i} \quad (5)$$

Where Initial Hydrous Ethanol Consumption refers to hydrous ethanol consumption, measured in liters, for each microregion in 2015, and Initial Gasoline Consumption refers to gasoline consumption, also measured in liters, for each microregion in 2015. It is worth noting that 2015 predates the treatment of the first treated microregion, which received its first full plant in 2017. Information on the consumption of each fuel was obtained from the ANP. Corn production, in turn, was measured as the quantity of corn produced, in tons, in each microregion, also in 2015, such that:

$$Corn_i = \log(Corn\ Production_i) \quad (6)$$

Where Corn Production represents the quantity of corn produced, measured in tons, in each microregion in 2015. Information on corn production was obtained from the Brazilian Institute of Geography and Statistics (IBGE). The IBGE annually conducts the Municipal Agricultural Production Survey (PAM), which collects data on a wide range of temporary and permanent crops across the country. The PAM provides information on planted area, area intended for harvest, harvested area, quantity produced, average yield, and the average price paid to producers in the reference year, covering 64 agricultural products, including corn.

4. Results

The analysis aims to assess the impacts of the implementation of the *full* model across microregions in Brazil's Center-West region. The estimates were obtained using doubly robust difference-in-differences models, considering as the control group the microregions that were never treated, that is, those without plants exclusively processing corn for ethanol production.

The first step of the evaluation consisted of estimating specific models for each combination of microregions belonging to the same cohort g (defined by the initial year of treatment) in each period t. Given the large number of estimates generated, this section presents the results based on two types of aggregation of the estimated parameters.

First, I report the average treatment effect across all groups, which represents the mean impact of the treatment on the variables of interest: relative ethanol consumption, per capita emissions, total employment, employment in the agricultural sector, employment in the industrial sector, and employment in the services sector. Next, I present estimates of the dynamic treatment effects over time. Specifically, I examine how the impact of the implementation of a *full* plant evolves in each period relative to the onset of treatment, allowing for the identification of both immediate and medium to long-term effects. These results are presented through event study graphs, which illustrate the temporal trajectory of the estimated effects before and after treatment adoption.

Table II: Overall Treatment Effect Estimates - Full

Treatment: Adoption of the flex model of corn ethanol production	Overall Treatment Effect (ATT)	Std. Error
Relative Ethanol Consumption	0.048***	0.013
Emissions Per Capita	0.119***	0.038
Overall Employment	0.043***	0.006
Rural Employment	0.033*	0.018
Industrial Employment	0.042*	0.023
Services Employment	0.067***	0.023

Source: Authors. ***: Statistically significant at the 1% level; **: Statistically significant at the 5% level; *: Statistically significant at the 10% level.

According to Table II, the overall average effect of the implementation of a *full* plant on relative ethanol consumption is 0.048, statistically significant at the 1% level. This result indicates that, on average, the implementation of a plant primarily processing corn led to an increase in relative ethanol consumption in treated microregions compared to what would have occurred in the absence of treatment. This finding is consistent with the potential of *full* plants to spatially decentralize ethanol competitiveness, which, when dependent exclusively on sugarcane, tends to be concentrated in locations where the feedstock is produced. In addition, the positive impact of implementing a *full* plant in a given region may indicate that these firms are tapping into previously underserved markets for biofuels.

The estimated average treatment effect for emissions is 0.119, also statistically significant at the 1% level. This result suggests that, on average, the implementation of *full* corn ethanol plants led to an increase of 11.9 percentage points in CO_2-equivalent emissions in treated microregions. This finding indicates that emission reductions resulting from the substitution of fossil fuels with ethanol, given the increase in production, are not sufficient to offset the potential increases associated with the production process of corn ethanol.

Among the possible explanations is the substantial and rapid expansion of production capacity in *full* plants. This rapid growth implies the installation of new infrastructure, increased demand for input and energy for production, and greater intensity in the commercialization and transportation of products and co-products, all of which contribute to higher emissions.

The economic dynamism resulting from the implementation of a *full* plant in a given microregion also helps explain the estimated average treatment effect on total employment, which is 0.043 and statistically significant at the 1% level. This result indicates that, on average, the implementation of *full* corn ethanol plants led to a 4.3 percentage point increase in employment in treated microregions. When analyzing employment by sector, the estimated average treatment effects are 0.033 for agricultural employment, 0.042 for industrial employment, and 0.067 for employment in the services sector.

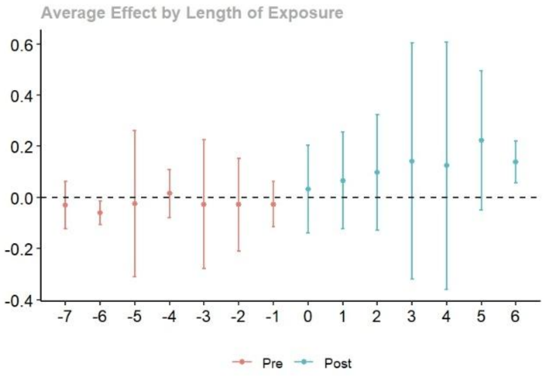
As previously discussed, *full* plants tend to be implemented in regions where corn production is already well established, due to the availability and price of the feedstock, as well as the governance strategies adopted by biofuel firms. Thus, the positive effect on agricultural employment is largely driven by two factors. First, there is an incentive to expand eucalyptus production, which is used as biomass for energy cogeneration in the production process. Second, there are potential spillover effects from the availability of DDGS, an important co-product used in animal feed. Depending on its energy performance and market prices, the availability of this co-product may strengthen local agricultural production, generating income and employment.

Finally, the implementation of a *full* plant also generates production linkages in both the industrial and services sectors. In the case of industrial employment, the plant itself creates local jobs, as do industries linked to the production process, including input supply and product distribution. In the services sector, logistics related to the transportation and commercialization of ethanol and its co-products play a key role. Unlike the *flex* model, which relies on already established logistics networks from sugarcane ethanol production, the *full* model requires the development of new structures that are not yet fully consolidated. Therefore, an expansion in employment related to transportation and distribution is expected. This is consistent with the finding that the largest sectoral impact is observed in the services sector.

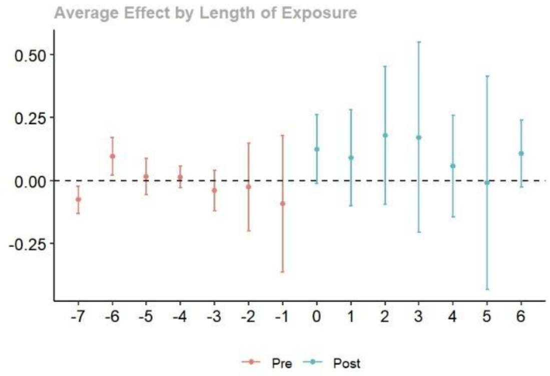
Figure 4 presents the dynamic treatment effects on relative ethanol consumption, emissions, and total employment. The red lines represent differences between treatment and control groups in the pre-treatment periods, while the blue lines illustrate the aggregated treatment effects in the post-treatment periods.

For relative ethanol consumption, pre-treatment estimates remain close to zero, with no clear trend and confidence intervals generally including zero. This pattern suggests the absence of significant pre-trends, supporting the validity of the empirical strategy and the plausibility of the parallel trends assumption. In the post-treatment period, coefficients follow an upward trajectory, becoming positive and increasing over time. This pattern indicates a gradual increase in relative ethanol consumption following the implementation of a *full* plant. Although confidence intervals remain wide in the early post-treatment periods, effects become more consistent and clearly positive over time. Overall, the results suggest that the implementation of a *full* plant is associated with a growing increase in ethanol consumption, likely reflecting gradual adjustments by consumers and the progressive expansion of production capacity.

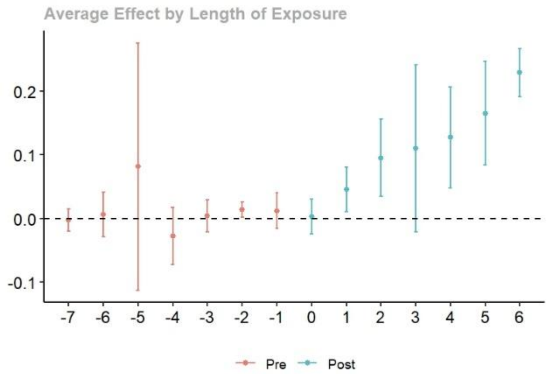
Figure 4: Event Study – Treatment: Adoption of the full model



(a) Relative Ethanol Consumption



(b) Emissions



(c) Overall Employment

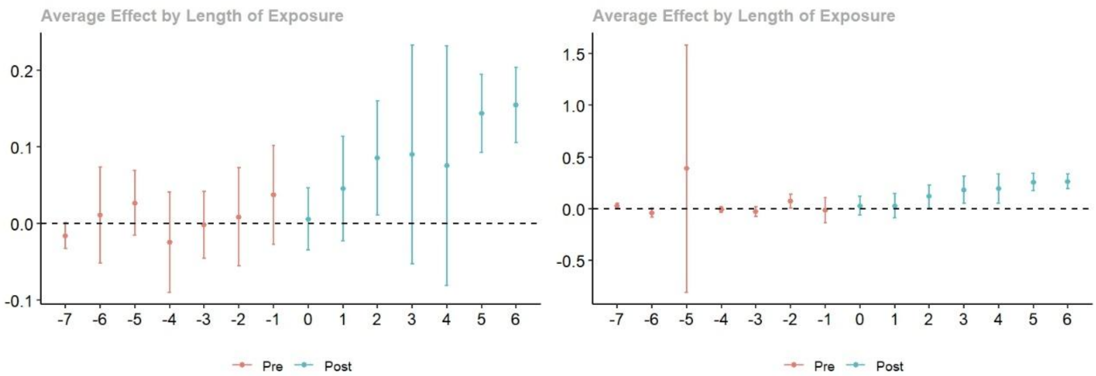
For emissions, a similar pattern is observed in the pre-treatment period, with coefficients fluctuating around zero and no systematic trend. Confidence intervals generally include zero, indicating no statistically significant differences prior to treatment. At the time of implementation, the estimated effect becomes positive, indicating an initial increase in emissions. In subsequent periods, the pattern remains relatively unstable but predominantly positive. In some periods (like 2 and 3), coefficients reach higher values, suggesting more pronounced increases in emissions. However, confidence intervals are wide, particularly in later periods, indicating greater uncertainty.

Overall, the results suggest that the implementation of a *full* plant is associated with an increase in greenhouse gas emissions, although this effect is not entirely stable over time and exhibits considerable variability, possibly reflecting operational adjustments, regional heterogeneity, or data limitations.

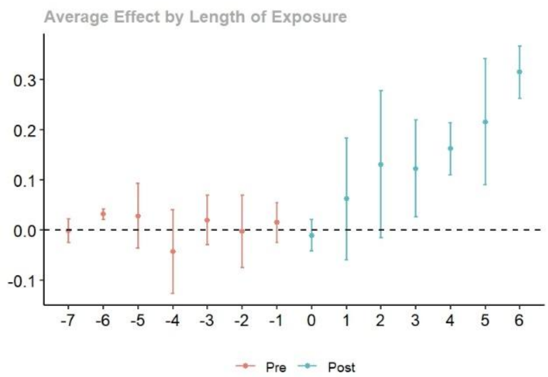
For employment, pre-treatment coefficients remain close to zero, with no evidence of systematic trends. Although there is some variation, particularly in period -5, confidence intervals generally include zero, indicating no statistically significant pre-treatment effects, consistent with the parallel trends assumption. At the time of implementation (period zero), the estimated effect is close to zero. In subsequent periods, coefficients follow an upward trajectory, becoming positive and increasing over time.

This pattern suggests that the implementation of a *full* plant is associated with a gradual increase in employment. In later periods (especially between 3 and 6), effects become larger and confidence intervals lie mostly above zero, indicating stronger statistical significance. These findings suggest that employment effects are not immediate but intensify over time, likely reflecting the expansion of productive activities and local spillovers.

Figure 5: Event Study– Treatment: Adoption of the flex model (Employment by sector)



(a) Rural Employment (b) Industrial Employment



(c) Services Employment

Figure 5 presents the dynamic effects on agricultural, industrial, and services employment. As in Figure 3, pre-treatment estimates are close to zero and show no systematic trend, supporting the parallel trends assumption. Confidence intervals are relatively wide both before and after treatment, likely due to the limited number of treated units.

For agricultural employment, the effect at implementation is close to zero, followed by a gradual increase in subsequent periods. Effects become more pronounced from period 2 onwards, although still accompanied by some uncertainty. Overall, the results suggest that the presence of a *full* plant is associated with an expansion in agricultural employment over time.

For industrial employment, the effect at implementation is small but positive, followed by a gradual and increasing trajectory over time. In later periods (especially between 3 and 6), effects become more pronounced and stable, with confidence intervals more consistently above zero. These results suggest that the impact on industrial employment materializes gradually, reflecting the expansion of productive activities and industrial linkages associated with the plant.

For services employment, effects are close to zero before treatment, supporting the parallel trends assumption, and remain negligible at implementation. Afterward, there is a gradual increase, with positive effects becoming more evident from around period 2 and strengthening in later periods (4 to 6), although some uncertainty persists. Overall, the results suggest that the presence of a full plant leads to a delayed but progressive expansion in services employment, likely driven by indirect spillover effects.

5. Final Considerations

This study evaluated the energy, environmental, and socioeconomic impacts of the adoption of full corn ethanol plants in Brazil's Midwest, using a doubly robust Difference-in-Differences approach applied to panel data from 2015 to 2023. The results indicate that the implementation of these plants contributes to an increase in relative ethanol consumption, suggesting an expansion in the competitiveness and availability of biofuels in regions historically less served by sugarcane-based production. This finding highlights the role of corn ethanol in reducing regional disparities in access to alternative fuels.

From an environmental perspective, the results show an increase in greenhouse gas emissions associated with the implementation of full plants. This suggests that the expansion of production capacity, along with the intensification of agricultural activity, energy use, and logistics, may outweigh the potential emissions reductions from substituting fossil fuels with ethanol. These findings reinforce the importance of considering the full production chain when assessing the environmental performance of biofuels, as well as the need for complementary policies aimed at mitigating emissions in the sector.

In socioeconomic terms, the adoption of full plants is associated with positive effects on employment, both in aggregate and across sectors. The results indicate that employment gains are not immediate but tend to intensify over time, reflecting the gradual expansion of productive activities and regional economic linkages. The stronger effects observed in the services sector suggest the relevance of indirect and spillover effects, particularly those related to logistics and distribution. Overall, the findings contribute to the literature by providing empirical evidence on the broader impacts of corn ethanol expansion and offer relevant insights for the design of energy and regional development policies.

An important limitation of this study concerns the relatively small number of treated units, which may affect the precision of the estimates and is reflected in the wide confidence intervals observed in some results. In addition, the analysis assumes the absence of spillover effects across microregions, although the installation of ethanol plants may generate impacts beyond local boundaries, potentially influencing neighboring areas. Data constraints also limit the inclusion of additional covariates that could capture other regional dynamics affecting the outcomes. Furthermore, the environmental analysis is restricted to aggregating greenhouse gas emissions, without distinguishing between different sources or stages of the production chain. These limitations suggest that the results should be interpreted with caution and indicate avenues for future research, particularly using more disaggregated data and alternative identification strategies.

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