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“Luiz de Queiroz” College of Agriculture

Essays on fuel policies in Brazil

Henrique dos Santos Maxir

Thesis presented to obtain the degree of Doctor in
Science. Area: Applied Economics

Piracicaba
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Bacharel em Ciências Econômicas

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Advisor:

Prof. Dr. **MIRIAN RUMENOS PIEDADE BACCHI**

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Dedication

To my parents, Sirley Felix dos Santos Maxir and Cicero Maxir Neto.

To my grandparents.

Francisca Felix dos Santos

Cícero José dos Santos

Maria do Carmo de Oliveira Maxir (*in memoriam*)

Francisco Maxir

Dedico aos meus pais, Sirley Felix dos Santos Maxir e Cicero Maxir Neto.

Dedico aos meus avós.

Francisca Felix dos Santos

Cícero José dos Santos

Maria do Carmo de Oliveira Maxir (*in memoriam*)

Francisco Maxir

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Abstract

Essays on fuel policies in Brazil

The Brazilian fuel market is an interesting case study. There are several policies regarding biofuels and fossil fuels. Since 1997, through Law No. 9,478 the called Oil Law, the oil industry permits the entry of foreign companies. In 2004, the establishment of the National Biodiesel Production and Use Program (PNPB) by Law No. 11,097 introduced the blend mandate of biodiesel in petroleum diesel. In 2017, Petrobras started a new pricing policy, frequently adjusting the fossil fuel prices and following the international level. In the same year, the government approved Law No. 13,576, creating the National Biofuel Policy (RenovaBio), which aims to reduce greenhouse gas (GHG) emissions with actions to expand biofuel production. The blend mandates of anhydrous ethanol in gasoline and between biodiesel and diesel play an important role since these policies combine fuel and food sectors such as sugar and soybeans. Thus, this thesis aims to evaluate complementary themes concerning fuel markets in Brazil through three essays. The first paper analyzes the oil industry between December 2002 and June 2017. We employ the New Empirical Industrial Organization (NEIO) model to assess demand and supply functions and the market power degree. The results show that the Brazilian oil industry is characterized as a monopoly in the analyzed period. The second paper examines the relationships between soybeans, biodiesel, and blended diesel (diesel C) sectors using data from January 2006 to December 2018. We use unrestricted and structural specifications of Vector Error Correction Models (VECMs) to evaluate: the linkages between prices of products of the soybean complex such as soybean grains, soybean meal, soybean oil, and biodiesel; the relationships between diesel, biodiesel, and soybean markets; and the demand for blended diesel. The estimates show that soybean prices from different locations in Brazil are important to determine the blended diesel price. An increase of 1% in petroleum diesel price impacts the diesel C price by 0.31-0.33%, while an equivalent expansion in biodiesel price decreases diesel C price by 0.22%-0.54%. The third paper measures the effects of several fuel policies on social welfare and GHG emissions. Through a partial equilibrium model concerning the sectors of gasoline, ethanol, biodiesel, diesel, other petroleum products, soybeans, and sugar, we evaluate different scenarios: *Status Quo** adopts current fuel policies; First-Best scenario assumes a competitive market and GHG emission tax applied by the government; and, RenovaBio policy combines the existing policies and carbon credits supplied by biofuel producers and purchased by fossil fuel industry. The First-Best policy results in the highest surplus with a welfare gain of 40.40% and -11.49% of GHG emissions if compared to *Status Quo**. The RenovaBio scenario produces -7.06% of GHG emissions, while welfare rises 0.31%, a gain of R\$ 6.43 billion in the Brazilian economy.

Keywords: Biofuel blend mandate; Fossil fuel; Greenhouse gas emissions; Social welfare.

Resumo

Ensaio sobre as políticas de combustíveis no Brasil

O mercado brasileiro de combustíveis é um interessante estudo de caso. Existem diversas políticas relacionadas aos biocombustíveis e combustíveis fósseis. Desde 1997, por meio da Lei 9.478, Lei do Petróleo, a indústria petrolífera permite a entrada de empresas estrangeiras. Em 2004, o estabelecimento do Programa Nacional de Produção e Uso do Biodiesel (PNPB) pela Lei 11.097 introduziu a mistura obrigatória de biodiesel no diesel. Em 2017, a Petrobras começou uma nova política de precificação, ajustando frequentemente os preços dos combustíveis fósseis, seguindo os níveis internacionais. No mesmo ano, o governo sancionou a Lei 13.576, criando a Política Nacional de Biocombustíveis (RenovaBio) com objetivo de reduzir emissões de gases de efeito estufa (GEE) com ações para expandir a produção de biocombustíveis. As políticas de mistura obrigatória de etanol anidro na gasolina e de biodiesel no diesel apresentam papel importante, pois relacionam os setores de combustíveis e alimentos, como açúcar e soja. Portanto, esta tese pretende avaliar temas complementares sobre os mercados de combustíveis no Brasil por meio de três ensaios. O primeiro artigo analisa a estrutura de mercado na indústria petrolífera entre dezembro de 2002 e junho de 2017. O modelo da Nova Organização Industrial Empírica (NOIE) é utilizado para determinar funções de demanda e oferta de petróleo, e o poder de mercado. Os resultados mostram que a indústria petrolífera brasileira é caracterizada como um monopólio no período analisado. O segundo artigo examina as relações entre os setores de soja, biodiesel e diesel misturado com biodiesel (diesel C), utilizando dados de janeiro de 2006 até dezembro de 2018. Foram usadas especificações irrestritas e estruturais de modelos de Vetor de Correção de Erros (*Vector Error Correction Models* - VECMs) para avaliar: as relações entre preços de produtos do complexo soja como grãos, farelo, óleo e biodiesel; as dependências entre os mercados de diesel, biodiesel e soja; e a demanda por diesel C. Os resultados indicam que preços de diferentes localidades brasileiras são importantes para determinar o preço do diesel C. O aumento de 1% no preço do diesel impacta o preço do diesel C em 0,31-0,33%, enquanto uma expansão de mesma magnitude no preço do biodiesel reduz o preço do diesel C em 0,22%-0,54%. O terceiro artigo mensura os efeitos de diversas políticas de combustíveis sobre o bem-estar econômico e emissões de GEE. A partir de um modelo de equilíbrio parcial que abrange os setores de gasolina, etanol, biodiesel, diesel, outros produtos de petróleo, soja e açúcar são avaliados diferentes cenários: *Status Quo** adota políticas atuais de combustíveis; *First-Best* assume um mercado competitivo e imposto sobre GEE aplicado pelo governo; e a política RenovaBio combina as políticas existentes e créditos de carbono ofertados pelos produtores de biocombustíveis e comprados pela indústria de combustíveis fósseis. O *First-Best* resulta no maior excedente, com ganho de bem-estar de 40,40% e -11,49% em emissões de GEE se comparado com *Status Quo**. A política RenovaBio resulta em -7,06% em emissões de GEE, enquanto o bem-estar econômico cresce 0,31%, um ganho de R\$ 6,43 bilhões na economia brasileira.

Palavras-chave: Mistura obrigatória de biocombustível; Combustível fóssil; Emissões de gases de efeito estufa; Bem-estar social.

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1. Introduction

In the 2000s and 2010s, the Brazilian fuel market experienced significant transformations due to new policies and technologies. In 2003, the new fleet of flex-fuel vehicles enabled consumers to use different combinations of gasohol and hydrous ethanol. In 2004, the National Biodiesel Production and Use Program (PNPB) established the obligatory blend of biodiesel in petroleum diesel. In 2007, the Pre-Salt oil reserves discovery was a milestone, reducing the Brazilian dependence on oil imports. In 2017, the main oil company in the country, Petrobras, announced a new pricing policy regarding fossil fuels, adjusting prices more often and following the international level. In the same year, it was launched the National Biofuel Policy (RenovaBio), aiming to reduce greenhouse gas (GHG) emissions, expand ethanol and biodiesel production, and decrease gasoline and diesel consumption.

These events are important to determine the future concerning fossil fuel and biofuel markets in Brazil. Furthermore, policies applied by the Brazilian government as a way to reduce GHG emissions can be used as an example for other developing economies. Thus, this thesis aims to analyze the fuel market in Brazil from three perspectives: market power degree, blend mandate of biodiesel and petroleum diesel, and the effects of fuel policies adopted in the country on GHG emissions and social welfare. The main research questions are as follows: Is the Brazilian oil industry characterized as a monopoly? Are soybean prices affecting the price of blended diesel? Is RenovaBio a good initiative to reduce GHG emissions? Can the RenovaBio policy generate welfare gains or deadweight loss in the Brazilian economy? To answer these questions, we divided this thesis into three papers.

The first paper objectives to evaluate the market power degree in the Brazilian oil industry considering the period from December 2002 to June 2017. We estimate supply and demand functions for oil and calculate the market power degree using the New Empirical Industrial Organization (NEIO) model. In the second paper, we aim to investigate the relationships between soybean, biodiesel, and blended diesel (diesel C) sectors in Brazil. We use time series ranging from January 2006 to December 2018 and employ unrestricted and structural specifications of Vector Error Correction Models (VECMs) to assess: i) the relationships between prices of products of the soybean complex as soybean grains, soybean meal, soybean oil, and biodiesel; ii) the linkages between diesel, biodiesel, and soybean markets; and iii) the demand for blended diesel. The third paper intends to measure the effects of several fuel policies on social welfare and greenhouse gas emissions in Brazil. For this purpose, we developed a partial equilibrium model concerning the markets of gasoline, ethanol, biodiesel, diesel, other petroleum

products, soybeans, and sugar. We observe the effects covering different scenarios, such as without government intervention (No Policy), current policies of 2016 (*Status Quo**), First-Best policy, including carbon tax imposed by the government on GHG emissions, and RenovaBio policy, assuming carbon credits supplied by biofuel producers and purchased by the fossil fuel industry. Additionally, we perform a sensitivity analysis adopting different elasticities from economic literature to evaluate the maximum and minimum effects on consumer and producer surpluses, government revenue, and emissions of carbon dioxide equivalent (CO₂e).

2. Is There Market Power in the Crude Oil Industry in Brazil?

Abstract

In 1997, the rupture of the Petrobras's monopoly in crude oil production and, in 2007, the discovery of oil reserves in Pre-Salt were important events for the Brazilian oil industry. These factors permitted the entry of other firms in the sector and the increase of national oil production. However, even with the recent advances, Brazil needs to import crude oil due to domestic oil characteristics. Therefore, this article aims to evaluate the market power degree in the Brazilian oil industry from December 2002 to June 2017, considering different types of crude oil. We use the model of the New Empirical Industrial Organization (NEIO). The results show that the NEIO model is adequate to evaluate market power. The Brazilian oil industry operated as a monopoly. The market power exercise was expressive in the analyzed period.

Keywords: Market power; NEIO; Demand; Supply; Monopoly.

2.1. Introduction

In Brazil, the oil industry changed considerably since the beginning of the 20th century. The development of the Brazilian oil sector is linked to the trajectory of Petrobras, the sole company responsible for implementing the state monopoly in oil extraction and production until 1997. The rupture of Petrobras's monopoly was an important event in the Brazilian oil industry (Brazil, 1997), enabling the entry of foreign companies into a strategic sector of the national economy. Although, after approximately 20 years, Petrobras is still the main oil company in Brazil.

In 2007, the discovery of Pre-Salt reserves placed the Brazilian oil industry under the spotlight of the government, companies, media, and economic literature (Petrobras, 2017). Several authors investigated different topics regarding the Brazilian oil industry applying various methodologies, such as Ortiz Neto and Costa (2007); Goldemberg and Lucon (2007); Campos (2014); and, Ramírez-Cendrero and Paz (2017).

The Pre-Salt reserves resulted in a reduction of the Brazilian dependence on imported oil. In 2005, the domestic oil production was 1.63 Million barrels per day (MMbbl/d), while in 2018, after the Pre-Salt, it was 2.59 MMbbl/d. The oil imports were 0.34 MMbbl/d in 2005, reducing to 0.19 MMbbl/d in 2018, while in the same period, the oil exports were 0.27 MMbbl/d, increasing to 1.15 MMbbl/d (OPEC, 2020). As a result, Brazil became a net oil exporter, but the country still needs to import fossil fuels because of the oil characteristics of national reserves. According to Goldemberg and Lucon (2007), the Brazilian oil self-sufficiency is physical, not

economic. The Brazilian oil does not have good quality, requiring imports of light oil (usually more expensive) to be processed in domestic refineries.

The Brazilian fuel market is formed by two segments: a) the market of fossil fuels such as gasoline, diesel, and other petroleum products; and, b) the market of biofuels such as ethanol and biodiesel. In the 1990s, the Brazilian ethanol sector was deregulated. There was no government intervention, and the sector had a greater number of producers if compared to the 1970s and 1980s. As a result, ethanol prices vary mainly due to sugarcane production and international sugar prices (Figueira et al., 2010; Moraes; Zilberman, 2014). Fossil fuel and biofuel markets are related because of three factors. First, the Brazilian Law No. 10,203 that establishes a mandatory blend of 27% of anhydrous ethanol in pure gasoline (Brazil, 2001). Second, the introduction of the new fleet of flex-fuel vehicles in Brazil since 2003, which allows a significant substitution between gasoline and hydrous ethanol (Salvo; Huse, 2013). Third, Law No. 11,097 that determines the blend mandate of 12% of biodiesel in petroleum diesel (Brazil, 2005).

The Brazilian economy has key characteristics that contribute to the growth of fuel markets: natural endowments of oil; adequate climate conditions for sugarcane cultivation to produce ethanol; sufficient soybean crop for biodiesel production; enormous flex-fuel fleet; consolidated ethanol sector; an expanding biodiesel industry; and increasing oil exploration. However, the fossil fuel pricing system in Brazil can affect consumers and generate economic inefficiencies nationwide.

The pricing policy of fossil fuels and its derivatives affects Petrobras's cash flow and the domestic economy, presenting impacts for shareholders and consumers. For example, in the gasoline sector, the Brazilian price did not follow gasoline or oil prices in the international market because of the presence of Petrobras (Khanna et al., 2016). However, in July 2017, Petrobras approved a new gasoline pricing policy, which defined that prices at refineries would undergo frequent readjustments according to the international price of gasoline and crude oil (Petrobras, 2018).

In Brazil and other countries in the world, the data concerning the oil industry is not fully available because of the strategic importance for business and national purposes. In some cases, it is possible to find estimates of lifting costs. According to Petrobras (2016), the production cost of one barrel of oil represents a small share of oil prices. In 2005, the average lifting cost in the Brazilian industry was 10.50% of Brent Europe oil price, representing US\$ 5.72 in the currency of 2005. In 2014, this indicator was 14.72%, US\$ 14.56 in values of 2014. Additionally, in the Brazilian oil sector, there is a share of the oil price that is directly allocated to the government. Thus, when oil prices grow in the international market, the amount received by the government

increases. In 2005, when Brent Europe oil price was US\$ 54.57 per barrel, the government received US\$ 8.99 per barrel (16.5%) and, in 2014, when this price reached US\$ 98.97, US\$ 15.97 per barrel (16.1%) was transferred to the government (Petrobras, 2016; EIA, 2018a).

Due to the lack of monthly information concerning the oil industry in Brazil, mainly regarding domestic oil price, extraction cost, transportation prices, and government shares, it becomes complex to assess the existence of some standard pricing system of oil in the country. It is difficult to specify the demand, the supply, and if there is market power exercise. The absence of public data concerning costs and factors that modify them creates uncertainty regarding the conduct of the firms in a market. The New Empirical Industrial Organization (NEIO) model is an alternative approach to solve these problems because it permits to measure the market power degree through demand and supply functions (Bresnahan, 1982).

The number of firms in a market is a key factor in the price setting. If the market is characterized as a monopoly (or cartel) or presents a concentrated structure, possibly the small number of participants implies in the market power exercise, that is, the price will be higher than the perfect competition level. However, if many firms are producing or trading in a sector, it is less likely that a single firm influences market prices (Church; Ware, 2000; Carlton; Perloff, 2005). In the Brazilian oil industry, Petrobras is the main producer due to the historical relationship with the government and the form of liberalization of fossil fuel production. Thus, this paper intends to fill a gap in the literature, where there is no estimate regarding own-price and income elasticities for oil demand in Brazil, as well as the market power exercise. Besides that, the Brazilian studies focused on assessing market power in the fuel distribution sectors, mainly ethanol and gasoline C (gasohol) such as Beiral et al. (2013), and Fernandes and Braga (2013). Therefore, this paper intends to answer the following research questions: What are the own-price and income elasticities of oil demand in Brazil? What is the elasticity of oil supply in Brazil? Is the Brazilian oil industry characterized as a monopoly according to the assumptions of neoclassical microeconomic theory? What is the market power degree in the Brazilian oil industry?

This research aims to evaluate the market power degree in the oil industry in Brazil between December 2002 and June 2017 using the NEIO model. There are three specific objectives: a) to estimate demand functions for oil; b) to assess supply relations of oil; and, c) to evaluate the market power degree. This research is justified due to the importance of oil industry in the country and its relationship with several sectors such as biofuel, transport, and agriculture. The analysis covers the period before the new pricing policy adopted by Petrobras in July 2017, and it is limited by data availability.

2.2. A brief history of Brazilian oil industry

In October 1953, Law No. 2,004 created Petrobras, establishing a state monopoly in the Brazilian oil industry. Petrobras was constituted as a joint company with limited shareholders, it was not allowed the ownership by foreign people, and international companies (Petrobras, 2016; Campos, 2014).

According to Campos (2014), in 1954, Petrobras received a set of machinery and equipment from the National Petroleum Council¹ (CNP) amounting to US\$ 165 million and investments of approximately US\$ 84 million. Besides, the company had several incentives such as tax exemptions on machinery and equipment imports and received capital from taxes charged on fuels, vehicle circulation, and imports of automobiles.

In 1961, Petrobras started to operate in the fuel retail sector, at gas station level, and in 1963, it was designated as a monopoly in the segment of oil imports. In 1964, the federal government became the main funding agent of Petrobras, obtaining and gathering national and international resources to develop the Brazilian oil industry, and promote the substitution of oil imports (Campos, 2014).

The 1970s were characterized by external shocks that resulted in the development of the national oil industry and a market of alternative energy sources. In 1973, the actions of the Organization of the Petroleum Exporting Countries (OPEC) resulted in a significant increase in the international prices of fossil fuels, the First Oil Shock (Chalabi, 1997; Adelman, 2004). According to Campos (2014), since Brazil was dependent on oil imports, there was a deficit in the trade balance summing US\$ 5 billion in 1973. In 1979, the Iranian revolution resulted in a significant reduction in world oil exports, causing an expressive rise in the international oil prices, called Second Oil Shock (Chalabi, 1997; Adelman, 2004). In this period, the Brazilian trade balance presented deficit, although the country had adopted policies to replace the oil imports such as the development of the National Alcohol Program² (Proálcool) in 1975 (Moraes; Zilberman; 2014).

In the 1970s, the process of petrodollar recycling allowed Brazil, with the Second National Development Plan³ (II PND), to obtain funds to invest in Petrobras's productive structure (Carneiro, 2002; Campos, 2014). However, the abundance of international financial resources ended in the early 1980s. Oil prices dropped, there was a surplus in the trade balance in 1984, and the scenario became favorable for imports of a large volume of oil since Saudi Arabia had entered

¹ In Portuguese, "Conselho Nacional do Petróleo (CNP)".

² In Portuguese, "Programa Nacional do Álcool (Proálcool)".

³ In Portuguese, "Segundo Plano Nacional de Desenvolvimento (II PND)".

into a price war with other OPEC members in 1986⁴. These factors contributed to a temporary reduction of the Brazilian deficit in trade balance (Campos, 2014).

In the 1980s, Petrobras discovered new oil reserves at Campos Basin (Rio de Janeiro State) such as Albacora, Marlim, and Barracuda oil fields. These reserves represented the possibility of an expressive reduction of the Brazilian dependence on oil imports in the middle term. Since offshore oil extraction technologies were limited, in 1986, Petrobras launched the Deep-water System Technological Innovation Program (PROCAP)⁵, which presented a key role in the development of offshore production systems (Leite, 2005; Ortiz Neto; Costa, 2007).

According to Petrobras (2016), since the 1980s, the company established four programs to develop offshore exploration technologies: i) from 1986 to 1991, PROCAP-1000 aimed to develop the oil production in the sea up to 1000 meters deep, in the Marlim and Albacora oil fields at Campos Basin; ii) in 1993, it was launched PROCAP-2000 to explore oil in the sea up to 2000 meters deep and to obtain tangible projects with a higher level of innovation; iii) in 2000, Petrobras created PROCAP-3000 to produce oil in ultra-deepwater up to 3000 meters; and, iv) in 2012, it was launched PROCAP “Visão Futuro” with the purpose of more efficient production and lower costs.

The Brazilian Constitution of 1988 reaffirmed the state monopoly in the oil sector, defining the National Petroleum Council (CNP) as the surveillance agency. Nevertheless, in the 1990s, the process of economic liberalization resulted in the extinction of several government agencies, the privatization of some strategic areas, and the flexibility of prices in various sectors (Carneiro, 2002; Filgueiras, 2012; Campos, 2014). Under the government of President Fernando Henrique Cardoso, the Brazilian oil industry has undergone important changes, it was established the rupture of Petrobras’s monopoly. On August 6, 1997, Law No. 9,478, called Oil Law, was announced to regulate the opening of oil exploration to the private sector. Thus, Petrobras ceased to be the sole executor of the state monopoly in the market of oil and natural gas in Brazil. The Oil Law also created the National Petroleum Agency (ANP), which administrates the government monopoly on exploration rights and production in the national territory (Brazil, 1997).

After 2002, with President Luiz Inácio Lula da Silva, the Brazilian oil sector lost prominence for some years. The industry of renewable energy sources was boosted, meaning the inclusion of biofuels as a new sector under ANP supervision, as defined in Law No. 11,097 of

⁴ In 1986, Saudi Arabia began to offer a large quantity of oil in the international market. The country adopted this strategy as a punishment action to other OPEC members that failed to comply with the agreements established within the organization (Maxir, 2016; Campos, 2014).

⁵ In Portuguese, “Programa de Capacitação Tecnológica em Águas Profundas (PROCAP)”.

2005 (Brazil, 2005). However, in 2007, the discovery of Pre-Salt reserves determined a change of preferences, the oil sector became the target of a great number of investments and, government support (Ramírez-Cendrero; Paz, 2017). This shift disagreed with the international requirements for the replacement of oil by alternative energy sources that present a lower volume of CO₂ emissions in the atmosphere. Brazilian oil production presented an upward trend over the last years, as shown in Figure 1.

Figure 1. Brazilian oil production and distribution between onshore and offshore (2000 - 2017)

Source: prepared by the authors according to data from ANP (2018).

The level of the Brazilian specialization on offshore oil extraction increased. In 2000, approximately 83.06% of the national oil extraction occurred in the sea, and, in 2017, it reached 95.15% (Figure 1). The concentration on offshore production is due to three factors: a) the investments in the Deep-water System Technological Innovation Program (PROCAP); b) the discovery of Pre-Salt reserves in 2007, which allowed the increase of oil production; and c); the shifts of Petrobras's investments towards the exploration and production sector, which the participation increased from 66.92% in 2005 to 82.97% in 2015 considering the total investments of the company (Petrobras, 2016).

The Oil Law of 1997 was amended in 2010, becoming effective three regimes regarding oil exploration rights in Brazil: a) Licensing system: the Law No. 9,478/97 establishes that areas of Post-Salt and considered non-strategic are designated for exploration through auctions; b) Production sharing: the Law No. 12,351/10 establishes that in Pre-Salt areas and other strategic locations the government can carry out auctions, where the winning companies must have Petrobras as an operating partner in at least 30% of production, the government owns the oil and gas produced, and the contractee has its investments and production costs offset; and c) Onerous transfer: it was created by Law No. 12,276/10, which establishes the possibility of direct transfer

of property rights from the federal government to Petrobras for oil research and exploration (Brazil, 1997; 2010a; 2010b). Table 1 shows information concerning the number of oil fields where Petrobras operates and the Concession Concentration Index (*CCI*) of exploration rights⁶.

Table 1. Productive oil fields in Brazil (12/31/2015)

Concessionaire company	Number of oil fields	Share (%)
Petrobras (100%)	286	77.09
Petrobras (<100%)	23	6.20
Petrosynergy	13	3.50
UTC Expl. E Prod.	5	1.35
Recôncavo E&P	5	1.35
Nova Petróleo Rec.	4	1.08
Central Resources	3	0.81
Alvopetro	3	0.81
OGX	2	0.54
Vipetro	2	0.54
Nord	1	0.27
Oceania	1	0.27
Severo Villares	1	0.27
IPI	1	0.27
EPG Brasil	1	0.27
Gran Tierra	1	0.27
Guto & Cacal	1	0.27
Santana	1	0.27
Egesa	1	0.27
Allpetro	1	0.27
Genesis 2000	1	0.27
Proen	1	0.27
Arclima	1	0.27
Joint concessions (without Petrobras)	12	3.23
Total	371	100.00
<i>CCI</i>		0.60
<i>CCI</i> ⁺		0.70

Source: prepared by the authors according to ANP (2018).

According to Table 1, even with the rupture of Petrobras's monopoly in the oil research and extraction in 1997, the company still has a predominant role, since it holds total participation (100%) in 77.09% of all fields under ANP's concession. Furthermore, the company is present in 6.20% of the fields with concession sharing (where Petrobras's share is less than 100%). The second company with the largest number of concessions is Petrosynergy, with 13 fields (3.50%).

⁶ The Concession Concentration Index (*CCI*) is an adaptation of the traditional index of Industrial Organization, the Herfindahl-Hirschman Index (*HHI*) as found in Church and Ware (2000). In this paper, the *CCI* can be defined as the sum of the squares of the concessionaire company share with respect to the total number of oil fields granted to all N firms in the Brazilian oil industry, that is, $CCI = \sum_{i=1}^N S_i^2$, where S_i is the share of the concessionaire firm i in the oil industry considering the total of exploration fields. The *CCI* ranges between zero, the lowest limit, indicating a non-concentrated concession pattern, and one (1), representing monopoly in concessions. Therefore, the closer to one (1) the more concentrated the concession system.

In Table 1, the Concession Concentration Index (CCI) was evaluated in two ways: 1) considering Petrobras as a decision-making agent only in the fields with full participation (100%); and, 2) summing the share of fields where Petrobras's share is 100% or less, it is assumed that Petrobras has decision-making power in the management of these fields, being the index denoted by CCI^+ . The indicators suggest a concentrated distribution of exploration and production rights in the Brazilian oil industry because of $CCI = 0.60$ and $CCI^+ = 0.70$ in 2015.

Since Pre-Salt discovery, the Brazilian oil reserves grew approximately 3% per year between 2007 and 2014. From 2012 to 2013, the growth achieved 14%. Worldwide, in 2014, Brazil had about 1% of proven oil reserves, while Saudi Arabia, the largest owner of oil reserves in the world, totaled 18% and the United States only 2% (OPEC, 2016; Petrobras, 2016; ANP, 2018). The oil production in Brazil increased because of the new reserves and investments in exploration. In 2014, Brazil, which historically presented difficulties to supply oil, produced approximately 3% of the world oil, while Saudi Arabia contributed with 13% and the United States with 12%. Figure 2 shows the recent evolution of oil production, exports, imports, and consumption in Brazil.

Figure 2. Production, imports, exports, and consumption of oil in Brazil (Dec. 2002 - Jun. 2017)
Source: prepared by the authors according to data from ANP (2018).

The oil imports presented expressive reduction over the years, from approximately 13 Million barrels (MMbbl) in December 2002 to 6 MMbbl in June 2017, while oil exports increased

from 8 MMbbl to 43 MMbbl in the same period, resulting in surpluses in the oil trade balance since 2007. Therefore, after more than 60 years of the establishment of Petrobras and 20 years of flexibility in the upstream sector, Brazil began to decrease its dependence on oil imports (Figure 2). In December 2002, the Brazilian oil consumption was about 46 MMbbl, achieving 42 MMbbl in June 2017. The oil consumption is meaningfully related to gasoline and diesel demand, as well as the hydrous ethanol market, the main substitute fuel for gasoline in Brazil.

National and international factors determine the unanticipated need for oil imports such as sugarcane harvests, the domestic price of ethanol, and the price of sugar in the Brazilian and international markets. Moreover, economies of scale, rigid import contracts, trade agreements, and quality of domestic oil can contribute to the Brazilian oil imports at higher prices than the international level. Figure 3 shows the Brazilian oil price, the average price paid by Brazil in the imported oil, and other international oil prices.

Figure 3. Crude oil prices (Dec. 2002 - Jun. 2017)

Source: prepared by the authors according to data from ANP (2018), EIA (2018a), and IMF (2018).

Note: the prices were deflated according to the All Commodity Price Index from IMF (2018), values expressed in US\$ of June 2017.

During December 2002 and June 2017, the average price of Europe Brent oil was US\$ 55.79 per barrel, and U.S. WTI was US\$ 54.37 per barrel. In the same period, the average price of imported oil by Brazil cost US\$ 59.65 per barrel, and the price of the Brazilian oil exported to the United States was US\$ 55.42. Thus, the Brazilian import price was US\$ 3.86 greater than the Europe Brent oil price, this discrepancy achieved US\$ 5.28 if compared to the WTI oil price.

2.3. Methodology

2.3.1. Static New Empirical Industrial Organization Model

The New Empirical Industrial Organization (NEIO) model was originated in the seminal work of Bresnahan (1982). This methodology was applied to study several Brazilian and international markets such as in Deodhar and Sheldon (1997) for world soybean meal exports; Genesove and Mullin (1998) for the refined sugar industry in the United States; Steen and Salvanes (1999) regarding Norway's market power in the fresh salmon market in French; Zeidan and Resende (2009) for the cement sector in Brazil; Beiral et al. (2013) for fuel ethanol distribution sector in Brazil; Fernandes and Braga (2013) in the gasoline C (gasohol) distribution sector in Brazil; and Lakuma (2013) for the crude oil industry in the United States. In the static NEIO model, the market power degree is obtained from demand and supply relations. Thus, given the inverse demand function (Bresnahan, 1982; 1989; Church; Ware, 2000; Maxir, 2016):

$$P_t = D(Q_t, Y_t, \delta, \varepsilon_{dt}) \quad (1)$$

where, P_t is the price, Q_t is the quantity, Y_t are exogenous variables that can change the demand curve (income, price of substitutes or complementary goods, seasonal dummies, etc.), δ are unknown parameters of demand that will be estimated, and ε_{dt} is the error term. We can calculate the total cost of firm i (TC_{it}) as:

$$TC_{it} = C_{it}(Q_{it}, W_{it}, \Gamma, \varepsilon_{cit}) \quad (2)$$

where, Q_{it} is the quantity produced by firm i , W_{it} are variables that shift the cost function (exogenous variables in supply such as the price of production factors, technology, seasonality, etc.), Γ are unknown parameters of the total cost function, and ε_{cit} is the error term. To minimize costs, the first-order condition is obtained as the derivative of the total cost function (2) with respect to the production level, resulting in the marginal cost of firm i (MC_{it}):

$$\frac{dTC_{it}}{dQ_{it}} = MC_{it} = C'_{it}(Q_{it}, W_{it}, \Gamma, \varepsilon_{cit}) \quad (3)$$

The profit of firm i (π_{it}) is calculated from the difference between total revenue and total cost:

$$\pi_{it} = D(Q_t, Y_t, \delta, \varepsilon_{dt})Q_{it} - C_{it}(Q_{it}, W_{it}, \Gamma, \varepsilon_{cit}) \quad (4)$$

The marginal revenue is the derivative of the first term on the right side of equation (4) with respect to Q_t :

$$MR_{it}(Q_t, Y_t, \delta, \lambda_{0i}) = P_t + \frac{dP_t}{dQ_t} Q_{it} \lambda_{0i} \quad (5)$$

where, λ_{0i} is the conduct parameter of firm i . From monopoly profit maximization, we equate the marginal revenue (5) to the marginal cost (3), resulting in the supply relation of firm i :

$$P_t = C'_{it}(Q_{it}, W_{it}, \Gamma, \varepsilon_{cit}) - \frac{dP_t}{dQ_t} Q_{it} \lambda_{0i} \quad (6)$$

where, $-dP_t/dQ_t$ is the slope. If the available information concerns the sector level, it is possible to determine the average conduct parameter of the industry (λ_0). Consequently, the supply relation will depend on the marginal cost of the industry, $C'_t(\cdot)$:

$$P_t = C'_t(Q_t, W_t, \Gamma, \varepsilon_{ct}) - \frac{dP_t}{dQ_t} Q_t \lambda_0 \quad (7)$$

According to Bresnahan (1982), and Steen and Salvanes (1999):

- a. If $\lambda_0 = 0$, firms are price takers, the price is equal to marginal cost, and the market is characterized as perfect competition;
- b. If $\lambda_0 = 1$, there is a monopoly or perfect cartel (with several firms acting in a perfectly coordinated way);
- c. If $0 < \lambda_0 < 1$, there is another oligopoly solution;
- d. If $-1 \leq \lambda_0 < 0$, there is market power exercise, but firms charge lower prices than those in perfect competition, there is a negative margin.

The demand curve and the supply relation are identified with the inclusion of exogenous variables in each equation because these variables allow shifts in demand and supply functions.

According to Church and Ware (2000), if price and quantity are endogenous variables, the order condition affirms that an equation is identified if the number of predetermined variables excluded from the equation is higher than or equal to the number of endogenous variables minus one. Therefore, the demand (supply) will be identified if there is an exogenous variable in the supply (demand) that is not present in the demand function (supply). Considering an inverse linear demand function given by:

$$P_t = \alpha_0 + \alpha_1 Q_t + \alpha_2 Y_{1t} + \alpha_3 Y_{1t} Q_t + \alpha_4 Y_{2t} \quad (8)$$

where, α are parameters that will be estimated, Y_{1t} is the price of a substitute good, and Y_{2t} is the income. The price of the substitute good (Y_{1t}) shifts the demand curve through α_2 and permits to determine the slope of demand with α_3 , the coefficient of the interaction variable $Y_{1t} Q_t$. The slope of demand function is $dP_t/dQ_t = \alpha_1 + \alpha_3 Y_{1t}$. The marginal cost of the industry is:

$$MC_t = \beta_0 + \beta_1 Q_t + \beta_2 W_{1t} \quad (9)$$

where, β are coefficients that will be estimated, and W_{1t} is an exogenous variable that shifts cost function, for example, the price of an input. Replacing $dP_t/dQ_t = \alpha_1 + \alpha_3 Y_{1t}$ and equation (9) in (7), we find the supply relation:

$$P_t = \beta_0 + (\beta_1 - \alpha_1 \lambda_0) Q_t - \alpha_3 \lambda_0 Y_{1t} Q_t + \beta_2 W_{1t} \quad (10)$$

The system of demand and supply is built using equations (8) and (10). Changes in Y_{2t} allows the shift of the demand curve, being possible to identify the supply relation. Likewise, variations in W_{1t} determine the demand curve. The estimate of the supply relation provides $\alpha_3 \lambda_0$, the coefficient of $Y_{1t} Q_t$, and the demand function generates the estimation of α_3 . Therefore, the ratio between these coefficients results in the estimate of the conduct parameter in the sector.

The market power identification is possible because of the inclusion of the interaction variable (Bresnahan, 1982; Zeidan; Resende, 2009). The rotation of the demand curve enables changes in marginal revenue. Consequently, the equilibrium price and quantity modify if firms

exercise market power at the industry level. If the marginal cost is constant, then $\alpha_3 = 0$, that is, it is not necessary to include an interaction variable, the demand function will be:

$$P_t = \beta_0 + (\beta_1 - \alpha_1 \lambda_0) Q_t + \beta_2 W_{1t} \quad (11)$$

The constant marginal cost assumption means that $\beta_1 = 0$ in equation (9). The market power degree will be determined by the ratio between the measurement of coefficient $\alpha_1 \lambda_0$, from supply relation, and the estimate of coefficient α_1 , from demand function.

2.3.2. Empirical literature review

The NEIO methodology is well accepted in the economic literature. The static and dynamic specifications have been applied in several countries for different industries. Table 2 shows the results of selected studies highlighting the model validity.

Deodhar and Sheldon (1997) evaluated the degree of imperfect competition in the international market of soybean meal using the static NEIO approach. The authors concluded that for 1966-1974, the period before the entry of Argentine firms into the soybean meal export market, the market power degree was $\lambda_0 = 0.04$, and after the entry, 1975-1993, the market power degree achieved $\lambda_0 = 0.00$. As a result, the soybean meal exports market was perfectly competitive.

Genesove and Mullin (1998) aimed to assess the market conduct in the sugar industry in the United States between 1890-1914 using the static NEIO model and different econometric specifications. They emphasize that NEIO models perform adequately since estimates of market power degree were close to the Lerner index (L) for the sugar industry in the country. The Lerner Index (L) was 0.10, while the NEIO model with linear demand, known production costs, and technology resulted in a market power degree of $\lambda_{03} = 0.10$. Including unknown production costs and technology, the market power degree achieved $\lambda_{01} = 0.03$, and with unknown production costs and known production technology, it was $\lambda_{02} = 0.03$. Therefore, the monopoly structure must be rejected, being the sugar industry in the United States close to the perfect competition from 1890 to 1914.

Table 2. Applied NEIO methodology

Author/Year	Objective	Model	Results		
Deodhar and Sheldon (1997)	Estimate the degree of market power in the world market for soybean meal exports.	Static NEIO methodology. Yearly data from 1966 to 1993. The model tests a possible structural break in the conduct parameter with the entry of firms from Argentina, in 1975, into the international soybean meal export market.	Before the entry of firms from Argentina into the soybean meal export market. Period 1966-1974.	$\lambda_0 = 0.04$	
			After the entry of firms from Argentina in the soybean meal export market. Period 1975-1993.	$\lambda_0 = 0.00$	
Genesove and Mullin (1998)	Test the application of the NEIO model for the refined sugar industry of the United States East Coast.	Static NEIO methodology and direct calculation of conduct parameter with the Lerner index (L). Quarterly data from 1890 to 1914.	Lerner index (L)	$L = 0.10$	
			Model with linear demand. Unknown production costs and technology.	$\lambda_{01} = 0.03$	
			Model with linear demand. Unknown production costs and known production technology.	$\lambda_{02} = 0.03$	
			Model with linear demand, known production costs, and known technology.	$\lambda_{03} = 0.10$	
Steen and Salvanes (1999)	Analyze the degree of market power of Norway in the French fresh salmon market.	Dynamic NEIO methodology. Quarterly data from 1981 to 1992.	Short-run	$\lambda_0 = -0.025$	
			Long-run	$\Lambda = -0.050$	
Böckem (2004)	Test the existence of OPEC cartel and different structures in the oil market.	Dynamic NEIO methodology with the simultaneous and sequential move approach. Monthly data between 03/1992 and 08/1997.	Simultaneous move model	$\Lambda = 0.018$	
			Sequential move model	$\Lambda = [0, 0.170]$	
Zeidan and Resende (2009)	Estimate the conduct parameter for the cement market of five Brazilian regions.	Dynamic NEIO methodology. Monthly data between 01/1991 and 12/2006.	Region	Short-run	Long-run
			Northern	$\lambda_0 = 0.322$	$\Lambda = 0.562$
			Northeast	$\lambda_0 = 0.159$	$\Lambda = 0.233$
			Southeast	$\lambda_0 = 0.030$	$\Lambda = 0.038$
			Southern	$\lambda_0 = 0.287$	$\Lambda = 0.224$
Beiral et al. (2013)	Estimate the market power in the fuel ethanol distribution sector in Brazil.	Static NEIO methodology and Lerner index (L) as Genesove and Mullin (1998). Monthly data from 01/2003 to 05/2010.	NEIO	$\lambda_0 = 0.028$	
			Lerner index (L)	$L = 0.011$	
Fernandes and Braga (2013)	Evaluate the market power degree in the gasoline C distribution sector in Brazil.	Dynamic NEIO methodology. Monthly data from 01/2002 to 12/2008.	Region	Short-run	Long-run
			Northern	$\lambda_0 = 0.302$	$\Lambda = 0.068$
			Northeast	$\lambda_0 = 0.004$	$\Lambda = 0.440$
			Southeast	$\lambda_0 = 0.011$	$\Lambda = 0.018$
			Southern	$\lambda_0 = 0.021$	$\Lambda = 0.209$
Lakuma (2013)	Measure the market power in the crude oil industry in the United States.	Static and Dynamic NEIO methodologies.	Midwest	$\lambda_0 = 0.011$	$\Lambda = 0.085$
			Period	Static	Dynamic
				Short-run	Long-run
			1986 - 2012	$\lambda_0 = -0.007$	$\lambda_0 = -0.0002$ $\Lambda = -0.074$
			1986 - 2012	$\lambda_0 = -0.081$	$\lambda_0 = -0.006$ $\Lambda = 0.490$
			2000 - 2012	$\lambda_0 = -0.044$	$\lambda_0 = -0.040$ $\Lambda = -0.37$

Source: prepared by the authors according to Maxir (2015, p. 113) and consulted literature.

Note: λ_0 = short-run market power degree; Λ = long-run market power degree; L = Lerner index; the long-run market power degree is obtained from dynamic NEIO approach, which is derived in Steen and Salvanes (1999).

Steen and Salvanes (1999) performed an analysis of market power regarding the French market of fresh salmon using quarterly data from 1981 to 1992. The authors proposed a dynamic NEIO model to evaluate the short and long-run market power degree⁷. There was market power

⁷ The dynamic NEIO uses Error-Correcting Models (ECM), allowing the inclusion of lagged variables that can capture the dynamic habit formation in demand, and cost adjustments in supply. Due to Steen and Salvanes's (1999) model construction, the short-run market power is $-1 < \lambda_0 < 0$, and the long-run market power is $-1 < \Lambda < 0$. If Λ and λ_0 are equal to zero, there is perfect competition in the long and short-run, respectively. If Λ and λ_0 are equal

exercise by Norway in the French market of fresh salmon in the short term, since $\lambda_0 = -0.025$. But in the long term, the market was competitive with $\Lambda = -0.050$. Norway exercised seasonal market power when fresh wild-caught salmon was not available. In the long run, that is, considering all over the years of analysis, there was no reason for market power exercise because of the presence of other producers such as Scotland and North America.

Böckem (2004) analyzed the international oil market between March 1992 and August 1997. The market power degree was measured through the dynamic NEIO model. The long-run market power estimate of the simultaneous move model was $\Lambda = 0.018$, while in the sequential move model it was $\Lambda = [0.000, 0.170]$. Comparing these results with theoretical frameworks, the authors concluded that the perfect competition and monopoly were not appropriate classifications of the international oil market. The assumption of OPEC as a price-leader cartel who competes with a competitive fringe (other oil-producing countries) was the best characterization for the period analyzed. Thus, the sequential move model presented the most reliable approximation on market structure.

Zeidan and Resende (2009) applied the dynamic NEIO to measure the market power in the Brazilian cement market using data from January 1991 to December 2006 for five Brazilian regions (Northern, Northeast, Southeast, Southern, and Midwest). As can be seen in Table 2, there was heterogeneity between the market power degree across Brazilian regions. In the Southeast region, the market power degree was small due to the presence of a greater number of firms operating in the cement market. In the Northern region, the market power degree was high because only one firm produced cement.

Beiral et al. (2013) measured the market power in the fuel ethanol distribution sector in Brazil employing the static NEIO model and Lerner index (L). From monthly data between January 2003 and May 2010, the authors found $\lambda_0 = 0.028$ and $L = 0.011$, indicating that there was no market power exercise on the Brazilian fuel ethanol distribution segment. On the other hand, Fernandes and Braga (2013) aimed to evaluate the market power degree in the distribution sector of gasoline C (gasohol, pure gasoline blended with anhydrous ethanol) using the dynamic NEIO model, and data ranging from January 2002 to December 2008 for five Brazilian regions (Northern, Northeast, Southeast, Southern, and Midwest). The results presented in Table 2 show that there was inexpressive market power of gasohol distributors in Brazil, the substitution of gasoline for hydrous ethanol in the country was an important limiting factor for the market power exercise.

to one, there is the market power exercise, the market is characterized as a monopoly in the long and short-run. More details can be found in Steen and Salvanes (1999).

Lakuma (2013) analyzed the market power in the crude oil industry in the United States through a dynamic NEIO model. The author carried out estimates considering three periods: 1986-2012, 1986-1999, and 2000-2012. Between 1999 and 2000, the oil industry in the United States experienced collusions, mergers, and acquisitions. Thus, the authors aimed to observe if these factors contributed to upsurge the market power. According to Table 2, the oil industry in the United States exercised market power between 2000 and 2012.

2.3.3. Data

Table 3 summarizes the information regarding our dataset. The analysis period is from December 2002 to June 2017, comprising 175 observations. We assume the price of imported oil by Brazil as a proxy for the Brazilian oil price, as well as the Brent Europe oil price and oil prices of the United States with different American Petroleum Institute (*API*) gravity, supposing that the type of oil is important to determine the Brazilian oil consumption, as postulated by Goldemberg and Lucon (2007).

The American Petroleum Institute (*API*) gravity is a scale referencing the density of oil, it is expressed in terms of *degrees API*. The *API* gravity is defined as the ratio between oil and water densities. In the oil industry, the oils with lower density (light oils) are preferred to higher density oils (heavy oils) because the light oils have superior quantities of hydrocarbons to be converted into gasoline (EIA, 2018a). The measuring scale is expressed as:

$$\text{degrees API} = \left(\frac{141.5}{SG \text{ at } 60^\circ F / 60^\circ F} \right) - 131.5 \quad (12)$$

where, *SG* is the specific crude oil gravity at 60° Fahrenheit (*F*). It is important to note that the *degrees API* scale varies inversely to density, light oils have greater *degrees API*, and heavy oils show lower *degrees API*. The *degrees API* scale is essential to determine the market value. EIA (2018b) classifies the crude oils as:

- i) *Light crude oil* > 38 *degrees API*;
- ii) 22 *degrees API* < *Intermediate crude oil* ≤ 38 *degrees API*;
- iii) *Heavy crude oil* ≤ 22 *degrees API*;

To model the demand and supply, we selected the quantity of oil consumption, the Brazilian Gross Domestic Product (GDP), the anhydrous ethanol price, the price of oil tanker freight, and the exchange rate. The description of each variable is shown in Table 3.

Table 3. Selected variables

Variable	Description	Source
$Poil_{IBR,t}$	Price of imported oil by Brazil in US\$ per barrel (US\$/bbl). Price expressed in US\$ dollars of June 2017 and deflated using the All Commodity Price Index (ACPI) from the International Monetary Fund (IMF), which considers energy and non-energy commodities. This price is a proxy of the Brazilian oil price (Marlim), since data availability is limited, and Brazil is a price taker in the international oil market.	ANP (2018) and IMF (2018)
$Poil_{BRE,t}$	Spot Brent Europe oil price in US\$/bbl. Price deflated using the ACPI and expressed in US\$ dollars of June 2017. This price is a proxy of the Brazilian oil price, assuming Brazil as a price taker in the international oil market.	EIA (2018a) and IMF (2018)
$Poil_{20,t}$	Oil price in the United States in US\$/bbl with American Petroleum Institute gravity (API gravity) equals to or less than 20.0°. Price deflated using the ACPI and expressed in US\$ dollars of June 2017.	
$Poil_{25,t}$	Oil price in the United States in US\$/bbl with API gravity from 20.1° to 25.0°. Price deflated using the ACPI and expressed in US\$ dollars of June 2017.	
$Poil_{30,t}$	Oil price in the United States in US\$/bbl with API gravity from 25.1° to 30.0°. Price deflated using the ACPI and expressed in US\$ dollars of June 2017.	
$Poil_{35,t}$	Oil price in the United States in US\$/bbl with API gravity from 30.1° to 35.0°. Price deflated using the ACPI and expressed in US\$ dollars of June 2017.	
$Poil_{40,t}$	Oil price in the United States in US\$/bbl with API gravity from 35.1° to 40.0°. Price deflated using the ACPI and expressed in US\$ dollars of June 2017.	
$Poil_{40.1,t}$	Oil price in the United States in US\$/bbl with API gravity greater than 40.0°. Price deflated using the ACPI and expressed in US\$ dollars of June 2017.	
$Qoil_t$	Quantity of consumed oil in Brazil measured in Million barrels (MMbbl), which is defined as the national oil production plus the oil imports minus oil exports.	ANP (2018)
GDP_t	Brazilian Gross Domestic Product (GDP) in Billions of Reais (R\$) of June 2017. The values were deflated according to the General Price Index – Domestic Availability (in Portuguese, Índice Geral de Preços - Disponibilidade Interna, IGP-DI).	BCB (2018) and FGV (2018)
Pe_t	Monthly average of weekly spot prices of anhydrous ethanol in São Paulo State in US\$ per barrel (US\$/bbl). Price deflated using the ACPI and expressed in US\$ dollars of June 2017. We used anhydrous ethanol price of São Paulo State because the region contributed to 57% of the Brazilian ethanol production between 2000 and 2014 (UNICA, 2016), being a reference for the national price.	CEPEA (2018) and IMF (2018)
Fre_t	Price of oil tanker freight in dollars per metric ton equivalent (US\$/mt). It represents the average price of all major routes. Price deflated using the ACPI and expressed in US\$ dollars of June 2017.	OET (2018) and IMF (2018)
$Exrate_t$	Exchange rate (purchase) at the end of the period, in R\$/US\$.	BCB (2018)

Source: prepared by the authors.

Table 4 displays the descriptive statistics.

Table 4. Descriptive statics

Variable	Description	Units	Mean	Std. Dev.	Min.	Max
$Poil_{IBR,t}$	Price of imported oil by Brazil	US\$/bbl	59.65	8.12	38.48	83.88
$Poil_{BRE,t}$	Price of spot Brent Europe oil	US\$/bbl	55.79	6.49	39.41	66.39
$Poil_{20,t}$	Oil price with API gravity equals to or less than 20.0°	US\$/bbl	49.02	7.29	30.45	63.72
$Poil_{25,t}$	Oil price with API gravity from 20.1° to 25.0°	US\$/bbl	50.50	7.05	33.01	63.75
$Poil_{30,t}$	Oil price with API gravity from 25.1° to 30.0°	US\$/bbl	47.91	7.49	26.40	61.71
$Poil_{35,t}$	Oil price with API gravity from 30.1° to 35.0°	US\$/bbl	52.13	6.15	33.93	64.82
$Poil_{40,t}$	Oil price with API gravity from 35.1° to 40.0°	US\$/bbl	51.67	6.13	33.60	64.92
$Poil_{40.1,t}$	Oil price with API gravity greater than 40.0°	US\$/bbl	51.28	6.38	31.59	64.98
$Qoil_t$	Quantity of oil	Million barrels	55.51	7.04	37.49	81.39
GDP_t	Brazilian Gross Domestic Product	Billions R\$ of Jun. 2017	455.63	85.49	292.94	590.04
Pe_t	Price of anhydrous ethanol	US\$/bbl	155.60	69.00	61.93	424.28
Fre_t	Price of oil tanker freight	US\$/mt	9.69	6.99	2.13	30.15
$Exrate_t$	Exchange rate	R\$/US\$	2.40	0.63	1.56	4.04

Source: prepared by the authors.

In Table 4, the values consider the deflating indexes as described in Table 3. The price of imported oil by Brazil ($Poil_{IBR,t}$) is higher than other selected prices. The maximum difference is

US\$ 11.74 per barrel if compared $Poil_{IBR,t}$ to $Poil_{30,t}$, and the minimum discrepancy occurs when equating $Poil_{IBR,t}$ to $Poil_{BRE,t}$, the Europe spot price, achieving US\$ 3.86. In Appendix A, Figure A1 shows the time series considering the deflating indexes, being the prices expressed in US\$ of June 2017.

2.3.4. Empirical model

As described by Bresnahan (1982), the interaction variable allows the rotation of the demand curve. In our modeling, the interaction variables are defined as the multiplication of oil prices and anhydrous ethanol price:

$$I_{x,t} = Poil_{x,t}Pe_t \quad (13)$$

where, x denotes different oil prices used as proxies of the Brazilian oil price, being $x = (IBR, BRE, 20, 25, 30, 35, 40, 40.1)$. Therefore, the demand functions are:

$$Qoil_t = \omega_0 + \omega_1 Poil_{x,t} + \omega_2 Pe_t + \omega_3 GDP_t + \omega_4 I_{x,t} + \sum_{i=1}^n \gamma_i m_i + \varepsilon_1 \quad (14)$$

with $x = (IBR, BRE, 20, 25, 30, 35, 40, 40.1)$

where, m_i are seasonal monthly dummies, considering that from January to November, the dummies are equal to one ($i = 1, 2, \dots, 11$), and December is equal to zero, the baseline month; γ_i are coefficients of the dummy variables. The estimate regarding the demand function described in (13) provides the coefficients $\hat{\omega}_1$ and $\hat{\omega}_4$, enabling to calculate $Qoil_t^\phi$, which is an instrumental variable for each supply relation:

$$Qoil_t^\phi = -\frac{Qoil_t}{(\hat{\omega}_1 + \hat{\omega}_4 Pe_t)} \quad (15)$$

The supply relations are:

$$Poil_{x,t} = \Omega_0 + \Omega_1 Qoil_t + \Omega_2 Fre_t + \Omega_3 Exrate_t + \Omega_4 Qoil_t^\phi + \varepsilon_2 \quad (16)$$

The coefficients of the variable $Qoil_t^\phi$ are the estimates of the market power degree for the Brazilian oil sector, $\hat{\Omega}_4 = \lambda_0$. The system of equations is composed of demand functions presented in (14) and supply relations shown in (15). The method of Two-Stage Least Squares (2SLS) is used due to the endogeneity of the explanatory variables in the structural model, where $Poil_{x,t}$ and $Qoil_t$ are endogenous, and GDP_t , Pe_t , $I_{x,t}$, m_i , Fre_t , $Exrate_t$, and $Qoil_t^\phi$ are exogenous variables. We expect to find coefficients with positive signals for $Qoil_t$, GDP_t , Pe_t , and Fre , and negative signal for $Poil_{x,t}$. We employ the free software RStudio 1.2.1578 for our modeling.

2.4. Results

To estimate the market power degree in the Brazilian oil industry, we followed the procedure outlined by Steen and Salvanes (1999); Böckem (2004); Zeidan and Rezende (2009); Fernandes and Braga (2013); and Lakuma (2013). First, it is necessary to test the stationarity of the time series. We use two different unit root tests: a) Dickey-Fuller Generalized Least Squares test (DF-GLS) with the null hypothesis of non-stationarity of the time series ($H_0: x_t \sim I(1)$), against the alternative of stationarity ($H_1: x_t \sim I(0)$) (Elliot et al., 1996); and, b) Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) test with the null hypothesis of stationarity of the time series ($H_0: x_t \sim I(0)$), against non-stationarity ($H_1: x_t \sim I(1)$) (Kwiatkowski et al., 1992).

Second, to check the existence of long-run relationships between variables in demand and supply, we apply multivariate cointegration tests such as Maximum Eigenvalue and Trace (Johansen, 1988; Johansen; Juselius, 1990). Third, the demand and supply are assessed using the method of Two-Stage Least Squares (2SLS) with instrumental variables (Bresnahan, 1982; Steen; Salvanes, 1999). This specification solves the problem of simultaneity when evaluating demand and supply equations (Hsiao, 1997). The Wu-Hausman test is used for endogeneity, guaranteeing the effectiveness of the models (Wooldridge, 2002; Greene, 2012). Fourth, according to the “impossibility theorem” of Lau (1982), it is difficult to identify the market power degree using the NEIO model if the inverse demand function is separable in a vector of exogenous variables. The coefficient estimate of the interaction variable must be statistically different from zero. Thus, to verify the validity of instruments, we employ the Weak Instruments test with the null hypothesis of weak instruments (Stock; Yogo, 2002; Greene, 2012; Fernandes; Braga, 2013).

Finally, we build confidence intervals to ensure the economic rationale of our estimates concerning the market power degree. If the market power degree is equal to zero, there is perfect

competition. The monopoly (or perfect cartel) occurs when the market power degree is equal to one. And, if it is less than zero, there is a negative margin (Steen; Salvanes, 1999; Church; Ware, 2000; Greene, 2012).

Table 5 summarizes the results regarding unit root tests. The KPSS unit root tests indicate that all series, except $Qoil_t$, are non-stationary in the specification with the trend. The KPSS tests with constant present different results, $Qoil_t$ is non-stationary, as well as $Poil_{40,t}$, $Poil_{40.1,t}$, Pe_t , GDP_t , Fre_t , $Poil_{IBR,t}Pe_t$, $Poil_{BRE,t}Pe_t$, $Poil_{20,t}Pe_t$, $Poil_{25,t}Pe_t$, $Poil_{30,t}Pe_t$, $Poil_{35,t}Pe_t$, $Poil_{40,t}Pe_t$, and $Poil_{40.1,t}Pe_t$. For DF-GLS unit root tests, all variables are non-stationary when including trend or constant, but $Poil_{40.1,t}$ seems to be stationary at 10% of significance. We assume the results of DF-GLS, all variables are $I(1)$, that is, non-stationary at 5% of significance.

Table 5. KPSS and DF-GLS unit root tests

Variable	KPSS ^a		DF-GLS ^b	
	Trend statistic	Constant statistic	Trend statistic	Constant statistic
$Qoil_t$	0.090	0.891 ***	-1.082	-0.334
$Poil_{IBR,t}$	0.183 **	0.288	-1.209	-0.841
$Poil_{BRE,t}$	0.198 **	0.210	-1.550	-1.308
$Poil_{20,t}$	0.210 **	0.242	-1.343	-1.073
$Poil_{25,t}$	0.222 ***	0.252	-1.388	-1.099
$Poil_{30,t}$	0.229 ***	0.233	-1.411	-1.187
$Poil_{35,t}$	0.206 **	0.240	-1.409	-1.216
$Poil_{40,t}$	0.171 **	0.396 *	-1.682	-1.490
$Poil_{40.1,t}$	0.146 *	0.488 **	-1.862	-1.664 *
Pe_t	0.264 ***	0.444 *	-1.259	-1.226
GDP_t	0.229 ***	1.273 ***	-2.209	0.430
Fre_t	0.267 ***	0.975 ***	-1.481	-0.182
$Exrate_t$	0.310 ***	0.344	-0.347	-0.607
$Poil_{IBR,t}Pe_t$	0.261 ***	0.582 **	-1.459	-1.199
$Poil_{BRE,t}Pe_t$	0.271 ***	0.540 **	-1.205	-1.194
$Poil_{20,t}Pe_t$	0.269 ***	0.589 **	-1.007	-0.917
$Poil_{25,t}Pe_t$	0.270 ***	0.591 **	-1.040	-0.968
$Poil_{30,t}Pe_t$	0.264 ***	0.525 **	-1.064	-1.031
$Poil_{35,t}Pe_t$	0.277 ***	0.463 *	-0.972	-0.996
$Poil_{40,t}Pe_t$	0.276 ***	0.391 *	-0.988	-1.038
$Poil_{40.1,t}Pe_t$	0.282 ***	0.365 *	-0.926	-0.994

Source: prepared by the authors with RStudio 1.2.1578.

Note: *** significant at 1%; ** significant at 5%; * significant at 10%.

^a For KPSS, the critical values are from Kwiatkowski et al. (1992) - i) trend: 1% = 0.216, 5% = 0.146, and 10% = 0.119; ii) constant: 1% = 0.739, 5% = 0.463, and 10% = 0.347. 13 lags included.

^b For DF-GLS, the critical values are from MacKinnon (1991) - i) trend: 1% = -3.460, 5% = -2.930, and 10% = -2.640; ii) constant: 1% = -2.580, 5% = -1.940, and 10% = -1.620. 13 lags included.

The Johansen's (1988) procedure was adopted to verify the existence of long-run relationships between time series used in the demand and supply functions. First, we estimate unrestricted Vector Autoregression (VAR(p)) models using the Akaike Information Criterion (AIC) and 6 lags as maximum length to identify the appropriate lag order in the cointegration

tests. In Appendix B, Table B1 displays the optimal lag length for each specification. Tables B2, B3, B4, B5, and B6 show that, according to Maximum Eigenvalue and Trace tests, there is at least one cointegrating vector (a stationary long-run relationship) in the demand functions and supply relations.

Table 6 presents the Brazilian oil demand estimates. The significant coefficients are following the microeconomic theory, since the evaluated parameters for oil and anhydrous ethanol prices show negative signals, and there is a positive effect of the Gross Domestic Product. The positive coefficients regarding instrumental variables agree with Bresnahan's (1982, 1989) assumptions. The dummies coefficients show that the Brazilian oil demand tends to increase in May and October if compared to December, the baseline month.

Table 6. Estimates of Brazilian oil demand

Variable	Oil Prices ($Poil_{x,t}$)						
	$Poil_{BRE,t}$	$Poil_{20,t}$	$Poil_{25,t}$	$Poil_{30,t}$	$Poil_{35,t}$	$Poil_{40,t}$	$Poil_{40.1,t}$
	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
<i>Intercept</i>	86.016 *** (21.014)	73.115 *** (18.347)	75.100 *** (18.268)	62.221 *** (12.091)	74.712 *** (19.493)	83.658 *** (24.703)	84.048 *** (27.041)
$Qoil_t$	-1.074 ** (0.443)	-0.946 ** (0.460)	-0.947 ** (0.435)	-0.687 ** (0.305)	-0.889 ** (0.430)	-1.048 ** (0.523)	-1.050 * (0.565)
Pe_t	-0.339 *** (0.130)	-0.243 ** (0.121)	-0.257 ** (0.118)	-0.157 ** (0.069)	-0.237 ** (0.110)	-0.269 ** (0.132)	-0.259 * (0.136)
GDP_t	0.050 *** (0.008)	0.053 *** (0.008)	0.051 *** (0.008)	0.050 *** (0.007)	0.049 *** (0.007)	0.047 *** (0.006)	0.045 *** (0.006)
$Poil_{x,t}Pe_t$	0.007 *** (0.003)	0.005 * (0.003)	0.006 ** (0.003)	0.004 ** (0.002)	0.005 * (0.002)	0.006 ** (0.003)	0.005 * (0.003)
<i>Jan</i>	3.498 (2.712)	3.211 (2.721)	3.262 (2.663)	3.002 (2.655)	2.916 (2.634)	3.079 (2.757)	3.116 (2.808)
<i>Feb</i>	0.009 (2.820)	0.221 (2.958)	0.224 (2.902)	-0.102 (2.828)	-0.132 (2.853)	-0.149 (3.019)	-0.050 (3.073)
<i>Mar</i>	3.856 (3.856)	4.105 (4.105)	4.231 * (4.231)	3.863 (3.863)	3.929 (3.929)	4.068 (4.068)	4.126 (4.126)
<i>Apr</i>	3.067 (2.526)	3.240 (2.596)	3.310 (2.580)	3.130 (2.582)	3.103 (2.543)	3.228 (2.682)	3.259 (2.743)
<i>May</i>	4.343 * (2.401)	4.230 * (2.448)	4.321 * (2.410)	4.230 * (2.466)	4.193 * (2.492)	4.310 (2.610)	4.376 (2.674)
<i>Jun</i>	3.022 (2.774)	2.801 (2.857)	2.894 (2.834)	2.831 (2.831)	2.680 (2.805)	2.977 (2.950)	3.071 (3.024)
<i>Jul</i>	4.664 (3.019)	4.545 (3.088)	4.685 (3.088)	4.441 (3.074)	4.531 (3.117)	4.816 (3.262)	4.902 (3.296)
<i>Aug</i>	0.659 (2.655)	0.408 (2.707)	0.631 (2.717)	0.436 (2.761)	0.520 (2.838)	0.766 (2.932)	0.863 (3.006)
<i>Sep</i>	3.071 (2.537)	3.207 (2.632)	3.311 (2.624)	3.190 (2.666)	3.354 (2.711)	3.389 (2.779)	3.461 (2.857)
<i>Oct</i>	5.590 *** (2.300)	5.667 ** (2.373)	5.790 ** (2.373)	5.849 ** (2.401)	5.992 ** (2.439)	5.955 ** (2.549)	6.076 ** (2.611)
<i>Nov</i>	2.005 (2.451)	1.952 (2.545)	2.027 (2.509)	1.910 (2.516)	2.034 (2.518)	2.089 (2.676)	2.178 (2.752)
Statistic							
Weak Instruments	13.275 ***	9.133 ***	10.968 ***	17.423 ***	12.129 ***	7.926 ***	6.604 **
Wu-Hausman	7.578 **	6.323 **	7.721 ***	9.249 ***	7.426 ***	9.161 ***	8.993 ***
R ²	0.237	0.217	0.223	0.246	0.227	0.145	0.111
Adjusted R ²	0.165	0.143	0.150	0.175	0.154	0.065	0.027
F	6.961	6.782	6.768	6.885	6.741	6.195	6.001
F (p-value)	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Source: prepared by the authors with RStudio 1.2.1578.

Note: *** significant at 1%; ** significant at 5%; * significant at 10%; standard deviation in parenthesis.

The Weak Instruments test consists of an F-test on instruments in the first stage of 2SLS. The non-rejection of the null hypothesis means that the instruments are frail. In Table 6, the results confirm the rejection of the null hypothesis for all specifications, the instruments are not weak. The use of Instrumental Variables (IV) worsens the estimates when it is not needed to use it. The Wu-Hausman test checks if Ordinary Least Squares (OLS) and Instrumental Variables (IV) estimates are consistent, that is, it tests the endogeneity. The results indicate that there is evidence of endogeneity for most models, being IV the best fitting. The outcomes regarding the model with the price of imported oil by Brazil ($Poil_{IBR,t}$) show that endogeneity is not a problem, being OLS the best specification. However, the estimates for the model with $Poil_{IBR,t}$ are not reasonable, presenting non-significance in key coefficients. The results comparing OLS and IV models are presented in Tables B4, B6, B7, and B8 in Appendix B. The own-price elasticity, cross-price elasticity, and income elasticity are displayed in Table 7⁸.

Table 7. Own-price elasticity, cross-price elasticity, and income elasticity of oil demand in Brazil

Oil Prices ($Poil_{x,t}$)	ξ_{Poil_x}	ξ_{Poil_xPe}	ξ_{GDP}
$Poil_{BRE,t}$	-0.023	-0.105	0.410
$Poil_{20,t}$	-0.092	-0.063	0.436
$Poil_{25,t}$	-0.069	-0.071	0.418
$Poil_{30,t}$	-0.112	-0.041	0.407
$Poil_{35,t}$	-0.109	-0.062	0.405
$Poil_{40,t}$	-0.161	-0.061	0.386
$Poil_{40.1,t}$	-0.185	-0.060	0.373

Source: prepared by the authors with RStudio 1.2.1578.

Note: ξ_{Poil_x} = own-price elasticity; ξ_{Poil_xPe} = cross-price elasticity; and ξ_{GDP} = income elasticity.

According to Table 7, taking into account the Brent oil price in the spot market ($Poil_{BRE,t}$), which is an important price for Brazilian oil demand, an increase of 1% in this price decreases the Brazilian oil consumption in 0.023%. For oil prices concerning different *API* gravity, the own-price elasticities indicate that for light crudes, which exceed 38 degrees *API*, the Brazilian oil demand is more elastic. These estimates are close to those found for own-price elasticities in developed countries that are highly dependent on oil as shown by Cooper (2003) for Italy (−0.035), Japan (−0.071), Canada (−0.041), Spain (−0.087), and the United States (−0.061). Analyzing the oil price with annual data between 1960 and 2011, Hesary and Yoshino (2014) identified price elasticities of oil demand equal to −0.08 (1960-2011), −0.10 (1960-1980), and −0.05 (1980-2011). For Baumeister and Peersman (2013), the average price elasticity of

⁸ Following Steen and Salvanes (1999), the own-price elasticity is given by $\xi_{Poil_x} = [\hat{\omega}_1 + \hat{\omega}_4 \overline{Pe_t}] \cdot [\overline{Poil_{x,t}} / \overline{Qoil_t}]$, the cross-price elasticity is $\xi_{Poil_xPe} = [\hat{\omega}_2 + \hat{\omega}_4 \overline{Poil_{x,t}}] \cdot [\overline{Pe_t} / \overline{Qoil_t}]$ and the income elasticity is $\xi_{GDP} = [\hat{\omega}_3] \cdot [\overline{GDP_t} / \overline{Qoil_t}]$.

international oil demand is -0.26 , considering the period from 1974 to 2010, but for 2005-2010 this value oscillated between 0 and -0.44 . Carrying out literature research, Caldara et al. (2016) observed an average oil demand elasticity of -0.22 , being the minimum -0.92 , and the maximum -0.03 , while survey studies revealed an average of -0.24 , where the lowest value was -0.34 , and the highest was -0.02 . Caldara et al. (2019) observed the oil demand using monthly data from 1985 to 2015 and highlighted that an admissible set for own-price elasticity of oil demand is between -1 and 0. Their panel estimates ranged from -0.080 to -0.017 for price elasticity of international oil demand. The authors also presented results regarding a VAR model oscillating between -3.48 and -0.13 . According to Lakuma (2013), in the United States, the oil industry experienced a structural change, the price elasticity of oil demand was -1.57 (1986-1999), becoming -0.81 (2000-2012). This change means technological progress due to the replacement of oil with alternative energy sources such as natural gas, shale gas, and nuclear energy.

In Brazil, the oil industry coexists with the ethanol sector since the 1970s, suggesting, *a priori*, the substitution between fossil and renewable fuels by consumers. However, the estimates of cross-price elasticities concerning anhydrous ethanol price and the Brazilian oil demand are negative, indicating some level of complementarity between oil and anhydrous ethanol. Thus, an increase of 1% in anhydrous ethanol price results in a reduction between 0.041% and 0.105% in Brazilian oil consumption (Table 7). In the country, the anhydrous ethanol is blended with gasoline A (pure gasoline), resulting in gasoline C (gasohol). Law No. 13,033 in its fifth article establishes the obligatory mixture⁹: “The Executive branch may increase this percentage up to the limit of 27.5% since the technical viability is assured, or decrease it to 18%” (Brazil, 2014, p. 2)¹⁰. Therefore, the anhydrous ethanol consumption depends on the demand of the main oil derivative in Brazil, pure gasoline. Our findings reflect the Brazilian Law No. 13,033, indirectly, oil and anhydrous ethanol are complementary goods.

In Table 7, the income elasticities are positive and smaller than one. A rise of 1% in Brazilian income increases the national oil demand in 0.373%-0.436%. An income growth implies in a less than the proportional rise of oil consumption, this fossil fuel is a necessary good. These results are close to Lakuma’s (2013) findings, which evaluated the income elasticity of oil demand in the United States of 0.20 (1986-1999), and 0.31 (2000-2012). In Hesary and Yoshino (2014), the income elasticity of demand was 0.13, considering 1960-2011, 0.14 for 1960-1980, and 0.14

⁹ Law No. 8,723 of October 28, 1993, shows the evolution of the blend mandate of anhydrous ethanol and pure gasoline (Brazil, 1993).

¹⁰ In Portuguese, “O Poder Executivo poderá elevar o referido percentual até o limite de 27,5% (vinte e sete inteiros e cinco décimos por cento), desde que constatada sua viabilidade técnica, ou reduzi-lo a 18% (dezoito por cento)” (Brazil, 2014, p. 2).

regarding 1980-2011. Therefore, in Brazil, as well as in other countries, crude oil is a normal good.

Table 8 summarizes the results for the Brazilian oil supply. The supply estimates present significant coefficients, and all signs are adequate.

Table 8. Estimates of Brazilian oil supply

Variable	Oil Prices ($Poil_{x,t}$)							
	$Poil_{BRE,t}$	$Poil_{20,t}$	$Poil_{25,t}$	$Poil_{30,t}$	$Poil_{35,t}$	$Poil_{40,t}$	$Poil_{40.1,t}$	
	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	
$Intercept$	53.706 *** (4.067)	47.325 *** (4.863)	47.831 *** (4.431)	51.971 *** (3.644)	49.757 *** (3.570)	48.843 *** (3.881)	48.592 *** (3.997)	
$Qoil_t$	0.603 *** (0.076)	0.699 *** (0.099)	0.663 *** (0.094)	0.523 *** (0.070)	0.535 *** (0.081)	0.501 *** (0.089)	0.493 *** (0.091)	
$Exrate_t$	-10.558 *** (1.304)	-11.801 *** (1.357)	-11.277 *** (1.355)	-12.132 *** (0.675)	-10.355 *** (1.032)	-10.116 *** (1.344)	-10.266 *** (1.342)	
Fre_t	0.131 * (0.060)	0.143 * (0.080)	0.127 * (0.075)	0.215 *** (0.059)	0.320 *** (0.060)	0.458 *** (0.062)	0.536 *** (0.063)	
λ_0	6.664 *** (1.304)	6.452 *** (1.357)	5.642 *** (1.355)	2.493 *** (0.675)	3.489 *** (1.032)	3.583 *** (1.344)	3.529 *** (1.342)	
Statistic								
Weak Instruments	15.290 ***	13.600 ***	14.870 ***	19.730 ***	15.360 ***	14.310 ***	14.260 ***	
Wu-Hausman	64.700 ***	52.540 ***	55.140 ***	45.260 ***	54.940 ***	40.590 ***	33.700 ***	
R ²	0.522	0.492	0.529	0.658	0.530	0.497	0.505	
Adjusted R ²	0.511	0.480	0.518	0.650	0.519	0.485	0.493	
F	79.18	62.14	74.55	103.5	66.47	60.46	58.6	
F (p-value)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

Source: prepared by the authors with RStudio 1.2.1578.

Note: *** significant at 1%; ** significant at 5%; * significant at 10%; standard deviation in parenthesis.

In Table 8, the coefficients regarding oil quantity show a positive relationship between oil supply and oil prices. The slope of $Exrate_t$ means that an increase in the exchange rate (R\$/US\$) reduces the oil price in Brazil. Our outcomes on parameters related to the price of oil tanker freight suggest that the costs of oil transportation positively affect oil prices. These findings are adherent to the Brazilian oil industry since oil production occurs mainly in offshore fields, and Petrobras needs to use oil tanker ships, drilling vessels, and FPSOs ships (Floating, Production, Storage, and Offloading ships) in the distribution of oil (Petrobras, 2016).

Table 9 displays the own-price elasticity of oil supply¹¹. According to Table 9, a growth of 1% in the oil price expands the Brazilian supply between 0.023% and 0.168%. These elasticities agree to other results from economic literature. In Hesary and Yoshino (2014), the short-run price elasticity of international oil supply was equal to 0.24 between 1960 and 2011, while from 1960 to 1980, it was 0.05, and between 1980 and 2011, it reached 0.12.

¹¹ The price elasticity of oil supply is given by $\xi_s = [\Delta Q / \Delta P][\bar{Q} / \bar{P}]$. Thus, in our model, the price elasticity of oil supply is $\xi_{Qoil} = 1 / [\hat{\omega}_1 + (-1 / (\hat{\omega}_1 + \hat{\omega}_4 P e_t))]$.

Table 9. Own-price elasticity of oil supply

Oil Prices ($Poil_{x,t}$)	ξ_{Qoil}
$Poil_{BRE,t}$	0.023
$Poil_{20,t}$	0.085
$Poil_{25,t}$	0.066
$Poil_{30,t}$	0.105
$Poil_{35,t}$	0.102
$Poil_{40,t}$	0.148
$Poil_{40.1,t}$	0.168

Source: prepared by the authors with RStudio 1.2.1578.

Note: ξ_{Qoil} = price elasticity of oil supply.

Baumeister and Peersman (2013), with quarterly data from 1974 to 2010, found short-run oil supply elasticities ranging from slightly over 0 to 0.6 and, between 2005 and 2010, these elasticities were marginally above zero, achieving the maximum value of approximately 0.20. Considering studies between 1982 and 2015, Caldara et al. (2016) outlined short-run supply elasticities of oil ranging from 0 to 0.27, where the average value was 0.10. Caldara et al. (2019) assessed the oil supply through monthly data from 1985 to 2015 and emphasized that an acceptable set for oil supply elasticity is between 0 and 0.4. The authors showed oil supply elasticities between 0.021 and 0.081 for panel estimates, while the outcomes of VAR models ranged from 0 to 0.18.

In Table 8, the market power degree is significant, presenting a positive signal for each model. The estimates exhibit high coefficients, which is expected since Petrobras is the major company in the Brazilian oil industry. According to Nunn and Sarvary (2004), the use of the NEIO model in monopoly sectors is an opportunity to verify the model calibration regarding demand and supply. To validate our results concerning the market power degree in the Brazilian oil industry, we build a confidence interval on forecasted values of λ_0 , accounting to different significance levels. The results are presented in Table 10.

Table 10. Confidence intervals for market power degree in the Brazilian oil industry

Oil Prices ($Poil_{x,t}$)	Upper Limit			λ_0	Lower Limit		
	Level				Level		
	99%	95%	90%		90%	95%	99%
$Poil_{BRE,t}$	10.418	9.520	9.061	6.664	4.267	3.808	2.911
$Poil_{20,t}$	9.475	8.753	8.383	6.452	4.521	4.151	3.429
$Poil_{25,t}$	8.726	7.989	7.612	5.642	3.672	3.295	2.558
$Poil_{30,t}$	4.214	3.803	3.592	2.493	1.394	1.183	0.772
$Poil_{35,t}$	6.036	5.427	5.116	3.489	1.862	1.551	0.942
$Poil_{40,t}$	6.737	5.983	5.597	3.583	1.569	1.184	0.430
$Poil_{40.1,t}$	6.700	5.942	5.554	3.529	1.504	1.116	0.358

Source: prepared by the authors with RStudio 1.2.1578

In Table 10, some estimates concerning the market power degree are distant from the theoretical value such as in $Poil_{BRE,t}$, $Poil_{20,t}$, and $Poil_{25,t}$. However, in models concerning prices of intermediate and light oils (API gravity greater than 22°), there is statistical evidence of adequate calibration since the lower limits of the confidence intervals at 1% of significance reveals proximity to one in $Poil_{30,t}$, $Poil_{35,t}$, $Poil_{40,t}$, and $Poil_{40.1,t}$. To confirm these results, we apply hypothesis tests comparing unrestricted models and linearly restricted models. For our purposes, we test the perfect competition structure ($H_0: \lambda_0 = 0$) and monopoly structure ($H_0: \lambda_0 = 1$). The results are summarized in Table 11.

Table 11. Tests on Brazilian oil market structure (at 1% of significance)

Oil Prices ($Poil_{x,t}$)	Market structure					
	Perfect Competition - $H_0: \lambda_0 = 0$			Monopoly - $H_0: \lambda_0 = 1$		
	Statistic (Chisq)	Pr(>Chisq)	Conclusion	Statistic (Chisq)	Pr(>Chisq)	Conclusion
$Poil_{BRE,t}$	20.915	4.801E-06	Reject	15.109	1.015E-04	Reject
$Poil_{20,t}$	30.215	3.868E-08	Reject	21.575	3.403E-06	Reject
$Poil_{25,t}$	22.202	2.454E-06	Reject	15.029	1.059E-04	Reject
$Poil_{30,t}$	13.916	1.912E-04	Reject	4.991	0.025	Do not reject
$Poil_{35,t}$	12.447	4.186E-04	Reject	6.335	0.012	Do not reject
$Poil_{40,t}$	8.5658	3.425E-03	Reject	4.452	0.035	Do not reject
$Poil_{40.1,t}$	8.2189	4.146E-03	Reject	4.221	0.040	Do not reject

Source: prepared by the authors with RStudio 1.2.1578.

The results in Table 11 reject the perfect competition hypothesis in all models but do not reject the monopoly in $Poil_{30,t}$, $Poil_{35,t}$, $Poil_{40,t}$, and $Poil_{40.1,t}$. We conclude that even with the rupture of Petrobras's monopoly in oil extraction and production through the Oil Law in Brazil, there is evidence of a monopoly structure in the Brazilian oil industry. Our results agree with Khanna et al. (2016), which stated that Petrobras is a *de facto* monopoly. The company has an important role in fossil fuel markets in the country, Petrobras actions can affect the price of oil and its derivatives such as diesel and gasoline, as well as the prices in other sectors as ethanol, sugar, soybean, and biodiesel.

2.5. Conclusion

In Brazil, the Law No. 9,478, the Oil Law from 1997, established the state monopoly on oil research and production, rupturing the Petrobras's control and enabling the entry of other companies. But, after more than 20 years from this policy, Petrobras is still the main oil company in the country.

This paper evaluates the market power degree in the Brazilian oil industry using data from December 2002 to June 2017, covering the period before the new pricing policy adopted by

Petrobras in July 2017, which determined the frequent adjustments of fossil fuel prices considering the international prices of crude oil and its derivatives. Through the New Empirical Industrial Organization (NEIO) model, we assessed demand and supply functions and measured the market power degree considering different prices and types of crude oil. Our results on elasticities are close to the estimates found by the economic literature for other countries. In Brazil, the price elasticity of oil demand ranges between -0.023 and -0.185 , indicating a demand slightly elastic, while the income elasticity is between 0.373 and 0.436 , meaning that oil is a normal good. The cross-price elasticity between anhydrous ethanol and crude oil varies from -0.049 to -0.105 , demonstrating that a rise of 1% in anhydrous ethanol price decreases the oil consumption between 0.049% and 0.105% since oil is used on pure gasoline production, a complementary good of anhydrous ethanol in Brazil. The price elasticity of oil supply fluctuates from 0.023 to 0.168 in Brazil.

The information on elasticities can be used in the formulation of policies concerning fossil fuels and biofuels in Brazil, once known the response of crude oil consumption in relation to price, income, and alternative fuels such as anhydrous ethanol, the policymakers can forecast the average effects of new adjustments on oil prices. Additionally, the measurements regarding supply elasticity can determine the Brazilian oil production expansion given a price augmentation. Besides that, this paper fills a gap in the literature, assessing elasticities regarding the crude oil market in Brazil, enabling other researches to use this information as input in different types of models, such as general and partial equilibrium.

The market power assessment revealed that in the period before the new pricing policy of Petrobras, the market power exercise was huge. Thus, we reject the perfect competition market structure. Despite the Oil Law, Petrobras behaved as a *de facto* monopoly. This result implies that in the analyzed period, there was room for the possible political use of fossil fuel pricing policy. The price of crude oil and its derivatives, such as gasoline and diesel, could be adjusted when it was convenient for the main oil company, Petrobras, and the government, the major shareholder of Petrobras.

The static NEIO model is adequate to evaluate the market power since our results do not reject the hypothesis of monopoly in the oil industry in Brazil, as expected. We evaluated the short-run elasticities concerning the oil demand and supply in Brazil. However, this paper presents some limitations because it does not analyze elasticities and market power in the long-run. Moreover, it does not measure the possibility of structural change in the oil industry after the Petrobras's new pricing policy of fossil fuels in July 2017. Thus, we suggest as future studies the assessment of supply, demand, and market power degree in the long-run for the crude oil market

in Brazil, as well as the impact evaluation of a probable structural change in this market due to the new system of fossil fuel pricing in the country.

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2.7. Appendix A: figures of chapter 2

Figure A1. Time series in level (Dec. 2002 - Jun. 2017)

Source: prepared by the authors with RStudio 1.2.1578.

Figure A2. Time series in the first difference (Dec. 2002 - Jun. 2017)
 Source: prepared by the authors with RStudio 1.2.1578.

2.8. Appendix B: tables of chapter 2

Table B1. Lag-order selection in VAR(p)

Equation	Model with oil price ($Poil_{x,t}$)							
	$Poil_{IBR,t}$	$Poil_{BRE,t}$	$Poil_{20,t}$	$Poil_{25,t}$	$Poil_{30,t}$	$Poil_{35,t}$	$Poil_{40,t}$	$Poil_{40.1,t}$
Demand								
Selected variables								
$Qoil_t$	x	x	x	x	x	x	x	x
$Poil_{IBR,t}$	x							
$Poil_{BRE,t}$		x						
$Poil_{20,t}$			x					
$Poil_{25,t}$				x				
$Poil_{30,t}$					x			
$Poil_{35,t}$						x		
$Poil_{40,t}$							x	
$Poil_{40.1,t}$								x
Pe_t	x	x	x	x	x	x	x	x
GDP_t	x	x	x	x	x	x	x	x
$I_{x,t}$	x	x	x	x	x	x	x	x
Deterministic regressor								
None	3	3	3	3	3	3	3	3
Constant	1	3	3	3	3	3	3	3
Trend	1	3	3	3	3	3	3	3
Supply								
Selected variables								
$Poil_{IBR,t}$	x							
$Poil_{BRE,t}$		x						
$Poil_{20,t}$			x					
$Poil_{25,t}$				x				
$Poil_{30,t}$					x			
$Poil_{35,t}$						x		
$Poil_{40,t}$							x	
$Poil_{40.1,t}$								x
$Qoil_t$	x	x	x	x	x	x	x	x
$Exrate_t$	x	x	x	x	x	x	x	x
$Qoil_t^\phi$	x	x	x	x	x	x	x	x
Fre_t	x	x	x	x	x	x	x	x
Deterministic regressor								
None	2	2	2	2	2	3	2	2
Constant	1	2	2	2	2	2	2	2
Trend	2	2	2	2	2	3	2	2

Source: prepared by the authors with RStudio 1.2.1578.

Table B2. Cointegration tests for variables of oil demand (I)

Hypotheses		Model with oil price ($Poil_{x,t}$)															
H_0	H_1	$Poil_{IBR,t}$				$Poil_{BRE,t}$				$Poil_{20,t}$				$Poil_{25,t}$			
		Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%
Trace																	
None																	
$r = 4$	$r > 4$	1.67	6.50	8.18	11.65	2.30	6.50	8.18	11.65	1.82	6.50	8.18	11.65	1.84	6.5	8.18	11.65
$r = 3$	$r > 3$	10.74	15.66	17.95	23.52	9.83	15.66	17.95	23.52	10.42	15.66	17.95	23.52	10.51	15.66	17.95	23.52
$r = 2$	$r > 2$	30.99 *	28.71	31.52	37.22	24.36	28.71	31.52	37.22	31.10 *	28.71	31.52	37.22	30.64 *	28.71	31.52	37.22
$r = 1$	$r > 1$	70.74 ***	45.23	48.28	55.43	49.89 **	45.23	48.28	55.43	55.70 ***	45.23	48.28	55.43	57.92 ***	45.23	48.28	55.43
$r = 0$	$r > 0$	120.68 ***	66.49	70.60	78.87	101.47 ***	66.49	70.60	78.87	107.14 ***	66.49	70.60	78.87	108.85 ***	66.49	70.6	78.87
Constant																	
$r = 4$	$r > 4$					5.49	7.52	9.24	12.97	5.84	7.52	9.24	12.97	6.09	7.52	9.24	12.97
$r = 3$	$r > 3$					13.70	17.85	19.96	24.60	14.87	17.85	19.96	24.60	15.01	17.85	19.96	24.6
$r = 2$	$r > 2$					28.44	32.00	34.91	41.07	35.55 **	32.00	34.91	41.07	35.15 **	32	34.91	41.07
$r = 1$	$r > 1$					53.99 **	49.65	53.12	60.16	60.24 ***	49.65	53.12	60.16	62.48 ***	49.65	53.12	60.16
$r = 0$	$r > 0$					105.62 ***	71.86	76.07	84.45	111.80 ***	71.86	76.07	84.45	113.5 ***	71.86	76.07	84.45
Trend																	
$r = 4$	$r > 4$					6.30	10.49	12.25	16.26	6.08	10.49	12.25	16.26	6.39	10.49	12.25	16.26
$r = 3$	$r > 3$					20.48	22.76	25.32	30.45	23.28 *	22.76	25.32	30.45	22.43	22.76	25.32	30.45
$r = 2$	$r > 2$					36.66	39.06	42.44	48.45	44.21 **	39.06	42.44	48.45	44.07 **	39.06	42.44	48.45
$r = 1$	$r > 1$					67.08 **	59.14	62.99	70.05	71.09 ***	59.14	62.99	70.05	72.75 ***	59.14	62.99	70.05
$r = 0$	$r > 0$					119.10 ***	83.20	87.31	96.58	122.87 ***	83.20	87.31	96.58	123.77 ***	83.2	87.31	96.58
Maximum Eigenvalue																	
None																	
$r = 4$	$r = 5$	1.67	6.50	8.18	11.65	2.30	6.50	8.18	11.65	1.82	6.50	8.18	11.65	1.84	6.5	8.18	11.65
$r = 3$	$r = 4$	9.07	12.91	14.90	19.19	7.52	12.91	14.90	19.19	8.60	12.91	14.90	19.19	8.67	12.91	14.9	19.19
$r = 2$	$r = 3$	20.25 *	18.90	21.07	25.75	14.54	18.90	21.07	25.75	20.68 *	18.90	21.07	25.75	20.13 *	18.9	21.07	25.75
$r = 1$	$r = 2$	39.76 ***	24.78	27.14	32.14	25.53 *	24.78	27.14	32.14	24.59	24.78	27.14	32.14	27.27 **	24.78	27.14	32.14
$r = 0$	$r = 1$	49.94 ***	30.84	33.32	38.78	51.58 ***	30.84	33.32	38.78	51.45 ***	30.84	33.32	38.78	50.93 ***	30.84	33.32	38.78
Constant																	
$r = 4$	$r = 5$					5.49	7.52	9.24	12.97	5.84	7.52	9.24	12.97	6.09	7.52	9.24	12.97
$r = 3$	$r = 4$					8.21	13.75	15.67	20.20	9.03	13.75	15.67	20.20	8.92	13.75	15.67	20.2
$r = 2$	$r = 3$					14.74	19.77	22.00	26.81	20.68 *	19.77	22.00	26.81	20.15 *	19.77	22	26.81
$r = 1$	$r = 2$					25.55	25.56	28.14	33.24	24.69	25.56	28.14	33.24	27.33 *	25.56	28.14	33.24
$r = 0$	$r = 1$					51.63 ***	31.66	34.40	39.79	51.57 ***	31.66	34.40	39.79	51.02 ***	31.66	34.4	39.79
Trend																	
$r = 4$	$r = 5$					6.30	10.49	12.25	16.26	6.08	10.49	12.25	16.26	6.39	10.49	12.25	16.26
$r = 3$	$r = 4$					14.18	16.85	18.96	23.65	17.19 *	16.85	18.96	23.65	16.04	16.85	18.96	23.65
$r = 2$	$r = 3$					16.18	23.11	25.54	30.34	20.93	23.11	25.54	30.34	21.65	23.11	25.54	30.34
$r = 1$	$r = 2$					30.42 *	29.12	31.46	36.65	26.88	29.12	31.46	36.65	28.67	29.12	31.46	36.65
$r = 0$	$r = 1$					52.02 ***	34.75	37.52	42.36	51.79 ***	34.75	37.52	42.36	51.03 ***	34.75	37.52	42.36

Source: prepared by the authors with RStudio 1.2.1578.

Note: cointegration tests with deterministic term in the cointegration vector; lag order equals to $p - 1$ considering the optimal lag length in the VAR(p) model in Table B1; critical values obtained from Osterwald-Lenum (1992).

Table B3. Cointegration tests for variables of oil demand (II)

Hypotheses		Model with oil price ($Poil_{x,t}$)																
H_0	H_1	$Poil_{30,t}$				$Poil_{35,t}$				$Poil_{40,t}$				$Poil_{40.1,t}$				
		Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	
Trace																		
None																		
$r = 4$	$r > 4$	1.79		6.50	8.18	11.65		1.70		6.50	8.18	11.65		1.86		6.50	8.18	11.65
$r = 3$	$r > 3$	10.15		15.66	17.95	23.52		10.36		15.66	17.95	23.52		11.35		15.66	17.95	23.52
$r = 2$	$r > 2$	29.92	*	28.71	31.52	37.22		31.75	**	28.71	31.52	37.22		32.31	**	28.71	31.52	37.22
$r = 1$	$r > 1$	53.00	**	45.23	48.28	55.43		58.09	***	45.23	48.28	55.43		57.96	***	45.23	48.28	55.43
$r = 0$	$r > 0$	102.79	***	66.49	70.60	78.87		109.66	***	66.49	70.60	78.87		112.10	***	66.49	70.60	78.87
Constant																		
$r = 4$	$r > 4$	5.58		7.52	9.24	12.97		5.99		7.52	9.24	12.97		6.03		7.52	9.24	12.97
$r = 3$	$r > 3$	14.47		17.85	19.96	24.60		14.93		17.85	19.96	24.60		15.82		17.85	19.96	24.60
$r = 2$	$r > 2$	34.25	*	32.00	34.91	41.07		36.36	**	32.00	34.91	41.07		36.78	**	32.00	34.91	41.07
$r = 1$	$r > 1$	57.50	**	49.65	53.12	60.16		62.86	***	49.65	53.12	60.16		62.64	***	49.65	53.12	60.16
$r = 0$	$r > 0$	107.35	***	71.86	76.07	84.45		114.45	***	71.86	76.07	84.45		116.85	***	71.86	76.07	84.45
Trend																		
$r = 4$	$r > 4$	6.36		10.49	12.25	16.26		6.91		10.49	12.25	16.26		6.61		10.49	12.25	16.26
$r = 3$	$r > 3$	21.19		22.76	25.32	30.45		22.00		22.76	25.32	30.45		22.98	*	22.76	25.32	30.45
$r = 2$	$r > 2$	43.96	**	39.06	42.44	48.45		47.20	**	39.06	42.44	48.45		45.24	**	39.06	42.44	48.45
$r = 1$	$r > 1$	67.90		59.14	62.99	70.05		73.73	***	59.14	62.99	70.05		73.90	***	59.14	62.99	70.05
$r = 0$	$r > 0$	118.44	***	83.20	87.31	96.58		125.97	***	83.20	87.31	96.58		129.15	***	83.20	87.31	96.58
Maximum Eigenvalue																		
None																		
$r = 4$	$r = 5$	1.79		6.50	8.18	11.65		1.70		6.50	8.18	11.65		1.86		6.50	8.18	11.65
$r = 3$	$r = 4$	8.36		12.91	14.90	19.19		8.67		12.91	14.90	19.19		9.49		12.91	14.90	19.19
$r = 2$	$r = 3$	19.77	*	18.90	21.07	25.75		21.39	**	18.90	21.07	25.75		20.95	*	18.90	21.07	25.75
$r = 1$	$r = 2$	23.08		24.78	27.14	32.14		26.34	*	24.78	27.14	32.14		25.65	*	24.78	27.14	32.14
$r = 0$	$r = 1$	49.79	***	30.84	33.32	38.78		51.57	***	30.84	33.32	38.78		54.15	***	30.84	33.32	38.78
Constant																		
$r = 4$	$r = 5$	5.58		7.52	9.24	12.97		5.99		7.52	9.24	12.97		6.03		7.52	9.24	12.97
$r = 3$	$r = 4$	8.89		13.75	15.67	20.20		8.94		13.75	15.67	20.20		9.79		13.75	15.67	20.20
$r = 2$	$r = 3$	19.78	*	19.77	22.00	26.81		21.44	*	19.77	22.00	26.81		20.96	*	19.77	22.00	26.81
$r = 1$	$r = 2$	23.25		25.56	28.14	33.24		26.50	*	25.56	28.14	33.24		25.86	*	25.56	28.14	33.24
$r = 0$	$r = 1$	49.86	***	31.66	34.40	39.79		51.59	***	31.66	34.40	39.79		54.22	***	31.66	34.40	39.79
Trend																		
$r = 4$	$r = 5$	6.36		10.49	12.25	16.26		6.91		10.49	12.25	16.26		6.61		10.49	12.25	16.26
$r = 3$	$r = 4$	14.84		16.85	18.96	23.65		15.09		16.85	18.96	23.65		16.37		16.85	18.96	23.65
$r = 2$	$r = 3$	22.77		23.11	25.54	30.34		25.20	*	23.11	25.54	30.34		22.26		23.11	25.54	30.34
$r = 1$	$r = 2$	23.94		29.12	31.46	36.65		26.52		29.12	31.46	36.65		28.65		29.12	31.46	36.65
$r = 0$	$r = 1$	50.54	***	34.75	37.52	42.36		52.24	***	34.75	37.52	42.36		55.25	***	34.75	37.52	42.36

Source: prepared by the authors with RStudio 1.2.1578.

Note: cointegration tests with deterministic term in the cointegration vector; lag order equals to $p - 1$ considering the optimal lag length in the VAR(p) model in Table B1; critical values obtained from Osterwald-Lenum (1992).

Table B4. Cointegration tests for variables of oil supply (I)

Hypotheses		Model with oil price ($Poil_{x,t}$)															
H_0	H_1	$Poil_{BR,t}$				$Poil_{BRE,t}$				$Poil_{20,t}$				$Poil_{25,t}$			
		Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%
Trace																	
None																	
$r = 4$	$r > 4$	3.11		6.50	8.18	11.65	2.24		6.50	8.18	11.65	2.07		6.50	8.18	11.65	
$r = 3$	$r > 3$	11.54		15.66	17.95	23.52	10.59		15.66	17.95	23.52	10.83		15.66	17.95	23.52	
$r = 2$	$r > 2$	39.36	***	28.71	31.52	37.22	24.62		28.71	31.52	37.22	32.20	**	28.71	31.52	37.22	
$r = 1$	$r > 1$	83.73	***	45.23	48.28	55.43	54.52	**	45.23	48.28	55.43	61.32	***	45.23	48.28	55.43	
$r = 0$	$r > 0$	165.34	***	66.49	70.60	78.87	130.94	***	66.49	70.60	78.87	131.45	***	66.49	70.60	78.87	
Constant																	
$r = 4$	$r > 4$						2.26		7.52	9.24	12.97	2.11		7.52	9.24	12.97	
$r = 3$	$r > 3$						10.75		17.85	19.96	24.60	11.04		17.85	19.96	24.60	
$r = 2$	$r > 2$						24.86		32.00	34.91	41.07	32.41	*	32.00	34.91	41.07	
$r = 1$	$r > 1$						54.84	**	49.65	53.12	60.16	61.60	***	49.65	53.12	60.16	
$r = 0$	$r > 0$						131.26	***	71.86	76.07	84.45	131.73	***	71.86	76.07	84.45	
Trend																	
$r = 4$	$r > 4$	6.82		10.49	12.25	16.26	7.45		10.49	12.25	16.26	7.66		10.49	12.25	16.26	
$r = 3$	$r > 3$	30.20	**	22.76	25.32	30.45	21.17		22.76	25.32	30.45	28.93	**	22.76	25.32	30.45	
$r = 2$	$r > 2$	64.69	***	39.06	42.44	48.45	44.92	**	39.06	42.44	48.45	52.92	***	39.06	42.44	48.45	
$r = 1$	$r > 1$	109.76	***	59.14	62.99	70.05	81.66	***	59.14	62.99	70.05	88.05	***	59.14	62.99	70.05	
$r = 0$	$r > 0$	192.61	***	83.20	87.31	96.58	159.17	***	83.20	87.31	96.58	159.36	***	83.20	87.31	96.58	
Maximum Eigenvalue																	
None																	
$r = 4$	$r = 5$	3.11		6.50	8.18	11.65	2.24		6.50	8.18	11.65	2.07		6.50	8.18	11.65	
$r = 3$	$r = 4$	8.43		12.91	14.90	19.19	8.35		12.91	14.90	19.19	8.76		12.91	14.90	19.19	
$r = 2$	$r = 3$	27.81	***	18.90	21.07	25.75	14.02		18.90	21.07	25.75	21.37	**	18.90	21.07	25.75	
$r = 1$	$r = 2$	44.37	***	24.78	27.14	32.14	29.91	**	24.78	27.14	32.14	29.12	**	24.78	27.14	32.14	
$r = 0$	$r = 1$	81.61	***	30.84	33.32	38.78	76.42	***	30.84	33.32	38.78	70.13	***	30.84	33.32	38.78	
Constant																	
$r = 4$	$r = 5$						2.26		7.52	9.24	12.97	2.11		7.52	9.24	12.97	
$r = 3$	$r = 4$						8.49		13.75	15.67	20.20	8.93		13.75	15.67	20.20	
$r = 2$	$r = 3$						14.11		19.77	22.00	26.81	21.37	*	19.77	22.00	26.81	
$r = 1$	$r = 2$						29.98	**	25.56	28.14	33.24	29.19	**	25.56	28.14	33.24	
$r = 0$	$r = 1$						76.42	***	31.66	34.40	39.79	70.13	***	31.66	34.40	39.79	
Trend																	
$r = 4$	$r = 5$	6.82		10.49	12.25	16.26	7.45		10.49	12.25	16.26	7.66		10.49	12.25	16.26	
$r = 3$	$r = 4$	23.37	**	16.85	18.96	23.65	13.72		16.85	18.96	23.65	21.26	**	16.85	18.96	23.65	
$r = 2$	$r = 3$	34.50	***	23.11	25.54	30.34	23.75	*	23.11	25.54	30.34	24.00	*	23.11	25.54	30.34	
$r = 1$	$r = 2$	45.06	***	29.12	31.46	36.65	36.73	***	29.12	31.46	36.65	35.13	**	29.12	31.46	36.65	
$r = 0$	$r = 1$	82.86	***	34.75	37.52	42.36	77.51	***	34.75	37.52	42.36	71.31	***	34.75	37.52	42.36	

Source: prepared by the authors with RStudio 1.2.1578.

Note: cointegration tests with deterministic term in the cointegration vector; lag order equals to $p - 1$ considering the optimal lag length in the VAR(p) model in Table B1; critical values obtained from Osterwald-Lenum (1992).

Table B5. Cointegration tests for variables of oil supply (II)

Hypotheses		Model with oil price ($Poil_{x,t}$)															
H_0	H_1	$Poil_{30,t}$				$Poil_{35,t}$				$Poil_{40,t}$				$Poil_{40.1,t}$			
		Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%
Trace																	
None																	
$r = 4$	$r > 4$	2.12	6.50	8.18	11.65	2.31	6.50	8.18	11.65	1.99	6.50	8.18	11.65	2.02	6.50	8.18	11.65
$r = 3$	$r > 3$	10.59	15.66	17.95	23.52	9.15	15.66	17.95	23.52	10.90	15.66	17.95	23.52	10.96	15.66	17.95	23.52
$r = 2$	$r > 2$	34.14 **	28.71	31.52	37.22	31.25 *	28.71	31.52	37.22	37.78 ***	28.71	31.52	37.22	38.02 ***	28.71	31.52	37.22
$r = 1$	$r > 1$	66.97 ***	45.23	48.28	55.43	62.18 ***	45.23	48.28	55.43	68.04 ***	45.23	48.28	55.43	68.47 ***	45.23	48.28	55.43
$r = 0$	$r > 0$	141.86 ***	66.49	70.60	78.87	118.92 ***	66.49	70.60	78.87	149.90 ***	66.49	70.60	78.87	147.55 ***	66.49	70.60	78.87
Constant																	
$r = 4$	$r > 4$	2.15	7.52	9.24	12.97	2.36	7.52	9.24	12.97	2.02	7.52	9.24	12.97	2.05	7.52	9.24	12.97
$r = 3$	$r > 3$	10.79	17.85	19.96	24.60	11.34	17.85	19.96	24.60	11.13	17.85	19.96	24.60	11.19	17.85	19.96	24.60
$r = 2$	$r > 2$	34.38 *	32.00	34.91	41.07	38.31 **	32.00	34.91	41.07	38.03 **	32.00	34.91	41.07	38.26 **	32.00	34.91	41.07
$r = 1$	$r > 1$	67.26 ***	49.65	53.12	60.16	71.80 ***	49.65	53.12	60.16	68.36 ***	49.65	53.12	60.16	68.77 ***	49.65	53.12	60.16
$r = 0$	$r > 0$	142.15 ***	71.86	76.07	84.45	160.65 ***	71.86	76.07	84.45	150.22	71.86	76.07	84.45	147.86 ***	71.86	76.07	84.45
Trend																	
$r = 4$	$r > 4$	7.35	10.49	12.25	16.26	6.83	10.49	12.25	16.26	7.51	10.49	12.25	16.26	7.61	10.49	12.25	16.26
$r = 3$	$r > 3$	30.54	22.76	25.32	30.45	27.19 **	22.76	25.32	30.45	30.81 ***	22.76	25.32	30.45	30.45 ***	22.76	25.32	30.45
$r = 2$	$r > 2$	56.17	39.06	42.44	48.45	54.78 ***	39.06	42.44	48.45	58.64 ***	39.06	42.44	48.45	58.84 ***	39.06	42.44	48.45
$r = 1$	$r > 1$	95.85	59.14	62.99	70.05	89.35 ***	59.14	62.99	70.05	95.73 ***	59.14	62.99	70.05	95.98 ***	59.14	62.99	70.05
$r = 0$	$r > 0$	171.33	83.20	87.31	96.58	146.30 ***	83.20	87.31	96.58	179.22 ***	83.20	87.31	96.58	177.30 ***	83.20	87.31	96.58
Maximum Eigenvalue																	
None																	
$r = 4$	$r = 5$	2.12	6.50	8.18	11.65	2.31	6.50	8.18	11.65	1.99	6.50	8.18	11.65	2.02	6.50	8.18	11.65
$r = 3$	$r = 4$	8.47	12.91	14.90	19.19	6.84	12.91	14.90	19.19	8.91	12.91	14.90	19.19	8.93	12.91	14.90	19.19
$r = 2$	$r = 3$	23.55 **	18.90	21.07	25.75	22.10 **	18.90	21.07	25.75	26.88 ***	18.90	21.07	25.75	27.07 ***	18.90	21.07	25.75
$r = 1$	$r = 2$	32.84 ***	24.78	27.14	32.14	30.92 **	24.78	27.14	32.14	30.26 **	24.78	27.14	32.14	30.44 **	24.78	27.14	32.14
$r = 0$	$r = 1$	74.89 ***	30.84	33.32	38.78	56.74 ***	30.84	33.32	38.78	81.86 ***	30.84	33.32	38.78	79.08 ***	30.84	33.32	38.78
Constant																	
$r = 4$	$r = 5$	2.15	7.52	9.24	12.97	2.36	7.52	9.24	12.97	2.02	7.52	9.24	12.97	2.05	7.52	9.24	12.97
$r = 3$	$r = 4$	8.65	13.75	15.67	20.20	8.98	13.75	15.67	20.20	9.11	13.75	15.67	20.20	9.14	13.75	15.67	20.20
$r = 2$	$r = 3$	23.59 **	19.77	22.00	26.81	26.97 ***	19.77	22.00	26.81	26.90 ***	19.77	22.00	26.81	27.07 ***	19.77	22.00	26.81
$r = 1$	$r = 2$	32.88 **	25.56	28.14	33.24	33.48 ***	25.56	28.14	33.24	30.32 **	25.56	28.14	33.24	30.52 **	25.56	28.14	33.24
$r = 0$	$r = 1$	74.89 ***	31.66	34.40	39.79	88.85 ***	31.66	34.40	39.79	81.86 ***	31.66	34.40	39.79	79.08 ***	31.66	34.40	39.79
Trend																	
$r = 4$	$r = 5$	7.35	10.49	12.25	16.26	6.83	10.49	12.25	16.26	7.51	10.49	12.25	16.26	7.61	10.49	12.25	16.26
$r = 3$	$r = 4$	23.20 **	16.85	18.96	23.65	20.36 **	16.85	18.96	23.65	23.30 **	16.85	18.96	23.65	22.84 **	16.85	18.96	23.65
$r = 2$	$r = 3$	25.62 **	23.11	25.54	30.34	27.59 **	23.11	25.54	30.34	27.83 **	23.11	25.54	30.34	28.39 **	23.11	25.54	30.34
$r = 1$	$r = 2$	39.68 ***	29.12	31.46	36.65	34.57 **	29.12	31.46	36.65	37.09 ***	29.12	31.46	36.65	37.14 ***	29.12	31.46	36.65
$r = 0$	$r = 1$	75.48 ***	34.75	37.52	42.36	56.95 ***	34.75	37.52	42.36	83.49 ***	34.75	37.52	42.36	81.31 ***	34.75	37.52	42.36

Source: prepared by the authors with RStudio 1.2.1578.

Note: cointegration tests with deterministic term in the cointegration vector; lag order equals to $p - 1$ considering the optimal lag length in the VAR(p) model in Table B1; critical values obtained from Osterwald-Lenum (1992).

Table B6. Cointegration tests for variables of oil supply
(III)

Hypotheses		Model with oil price ($Poil_{IBR,t}$) ^a				
H_0	H_1	Stat.		10%	5%	1%
Trace						
None						
$r = 4$	$r > 4$	3.11		6.50	8.18	11.65
$r = 3$	$r > 3$	11.53		15.66	17.95	23.52
$r = 2$	$r > 2$	39.38	***	28.71	31.52	37.22
$r = 1$	$r > 1$	83.78	***	45.23	48.28	55.43
$r = 0$	$r > 0$	165.39	***	66.49	70.60	78.87
Constant						
$r = 4$	$r > 4$					
$r = 3$	$r > 3$					
$r = 2$	$r > 2$					
$r = 1$	$r > 1$					
$r = 0$	$r > 0$					
Trend						
$r = 4$	$r > 4$	6.82		10.49	12.25	16.26
$r = 3$	$r > 3$	30.22	**	22.76	25.32	30.45
$r = 2$	$r > 2$	64.72	***	39.06	42.44	48.45
$r = 1$	$r > 1$	109.81	***	59.14	62.99	70.05
$r = 0$	$r > 0$	192.66	***	83.20	87.31	96.58
Maximum Eigenvalue						
None						
$r = 4$	$r = 5$	3.11		6.50	8.18	11.65
$r = 3$	$r = 4$	8.42		12.91	14.90	19.19
$r = 2$	$r = 3$	27.85	***	18.90	21.07	25.75
$r = 1$	$r = 2$	44.40	***	24.78	27.14	32.14
$r = 0$	$r = 1$	81.61	***	30.84	33.32	38.78
Constant						
$r = 4$	$r = 5$					
$r = 3$	$r = 4$					
$r = 2$	$r = 3$					
$r = 1$	$r = 2$					
$r = 0$	$r = 1$					
Trend						
$r = 4$	$r = 5$	6.82		10.49	12.25	16.26
$r = 3$	$r = 4$	23.40	**	16.85	18.96	23.65
$r = 2$	$r = 3$	34.51	***	23.11	25.54	30.34
$r = 1$	$r = 2$	45.08	***	29.12	31.46	36.65
$r = 0$	$r = 1$	82.86	***	34.75	37.52	42.36

Source: prepared by the authors with RStudio 1.2.1578.

Note: ^a the supply relation considers the construction of λ_0 using coefficients from OLS estimates for demand; cointegration tests with deterministic term in the cointegration vector; lag order equals to $p - 1$ considering the optimal lag length in the VAR(p) model in Table B1; critical values obtained from Osterwald-Lenum (1992).

Table B7. Demand with the price of imported oil by Brazil ($Poil_{IBR,t}$)

Variable	OLS		IV	
	$Poil_{IBR,t}$		$Poil_{IBR,t}$	
	Coefficient		Coefficient	
<i>Intercept</i>	45.691	***	78.727	***
	(9.660)		(20.212)	
<i>Qoil_t</i>	-0.197		-0.823	**
	(0.174)		(0.391)	
<i>Pe_t</i>	-0.101	*	-0.280	**
	(0.053)		(0.114)	
<i>GDP_t</i>	0.039	***	0.047	***
	(0.006)		(0.008)	
<i>Poil_{x,t}Pe_t</i>	0.002	*	0.005	**
	(0.001)		(0.002)	
<i>Jan</i>	2.579		2.560	
	(2.162)		(2.628)	
<i>Feb</i>	-0.394		-0.438	
	(2.174)		(2.410)	
<i>Mar</i>	3.997	*	3.757	
	(2.169)		(3.757)	
<i>Apr</i>	3.412		3.286	
	(2.170)		(2.349)	
<i>May</i>	4.750	**	4.710	*
	(2.207)		(2.546)	
<i>Jun</i>	2.885		2.974	
	(2.194)		(2.703)	
<i>Jul</i>	4.286	*	4.208	
	(2.226)		(2.937)	
<i>Aug</i>	0.039		0.496	
	(2.216)		(2.755)	
<i>Sep</i>	2.686		3.491	
	(2.216)		(2.700)	
<i>Oct</i>	5.787	***	6.085	***
	(2.201)		(2.274)	
<i>Nov</i>	2.120		2.731	
	(2.203)		(2.429)	
Statistic				
Weak Instruments test			12.960	***
Wu-Hausman test			2.726	
R ²	0.358		0.306	
Adjusted R ²	0.298		0.240	
F	5.914		8.196	
F (p-value)	1.18E-09		1.37E-13	
Own-price elasticity (ξ_{Poil})	0.102		-0.051	
Cross-price elasticity ($\xi_{Poil \times Pe}$)	0.031		0.049	
Income elasticity (ξ_{GDP})	0.318		0.387	

Source: prepared by the authors with RStudio 1.2.1578.

Note: *** significant at 1%; ** significant at 5%; * significant at 10%; standard deviation in parenthesis.

Table B8. Supply with the price of imported oil by Brazil ($Poil_{IBR,t}$)

Variable	IV1 ^a	IV2 ^b
	$Poil_{IBR,t}$ Coefficient	$Poil_{IBR,t}$ Coefficient
<i>Intercept</i>	41.201 *** (7.899)	40.665 *** (7.970)
$Qoil_t$	1.164 *** (0.165)	1.169 *** (0.166)
$Exrate_t$	-13.447 *** (1.747)	-13.430 *** (2.076)
Fre_t	4.601 *** (0.796)	0.334 ** (0.114)
λ_0	0.330 *** (0.113)	11.973 *** (2.076)
Statistic		
Weak Instruments test		8.041 ***
Wu-Hausman test		85.714 ***
R ²	0.1693	0.162
Adjusted R ²	0.1498	0.143
F	29.45	29.27
F (p-value)	2.20E-16	2.20E-16
Own-price elasticity of supply (ξ_{Qoil})	-0.115	0.048

Source: prepared by the authors with RStudio 1.2.1578.

Note: *** significant at 1%; ** significant at 5%; * significant at 10%; standard deviation in parenthesis; ^a IV1 model considers the construction of λ_0 using coefficients from OLS estimation for demand with the price of imported oil by Brazil ($Poil_{IBR,t}$); ^b IV2 model considers the construction of λ_0 using coefficients from IV estimation for demand with the price of imported oil by Brazil ($Poil_{IBR,t}$).

3. Soybean, Biodiesel, and Petroleum Diesel: New Relationships Due to the Biofuel Blend Mandate in Brazil

Abstract

In 2004, the environmental concerns on climate change resulted in the establishment of the National Biodiesel Production and Use Program (PNPB) in Brazil. The PNPB aims to reduce the level of greenhouse gas (GHG) emissions from petroleum diesel consumption and boost biodiesel production based on family farming and agribusiness. This policy determines the obligatory blend of biodiesel and petroleum diesel in the country. Brazilian biodiesel production uses soybean as the main raw material. Thus, this paper objectives to analyze the relationships between soybean, biodiesel, and blended diesel (diesel C) sectors in Brazil. We use unrestricted and structural specifications of Vector Error Correction Models (VECMs) to evaluate three important topics: i) the relationships between prices of products of the soybean complex such as soybean grains, soybean meal, soybean oil, and biodiesel; ii) the linkages between diesel, biodiesel, and soybean markets; and iii) the demand for blended diesel. We use data concerning diesel market, soybean complex, and income. The data comprise the period from January 2006 to December 2018. Our results regarding soybean complex show that a rise (reduction) of 1% in soybean meal price expands (decreases) biodiesel price between 3.40% and 5.17%, and if the price of soybean oil increases 1%, biodiesel price raises 1.96%. Because of the blend mandate policy, a shock of 1% in pure diesel price impacts the price of blended diesel by 0.31%-0.33%, while the growth of the same magnitude in biodiesel price decreases diesel C price by 0.22%-0.54%. From several econometric specifications, we observe that soybean prices from different locations in Brazil are important to determine the price of blended diesel. In the long-run, the income elasticity of the demand for blended diesel is 0.825.

Keywords: Elasticity; Diesel demand; SVECM; Biofuel; Fossil fuel.

3.1. Introduction

In 2004, the Brazilian government established the National Biodiesel Production and Use Program (PNPB) by Law No. 11,097, aiming to reduce the level of greenhouse gas (GHG) emissions from petroleum diesel consumption and boost biodiesel production based on family farming or agribusiness sectors (Brazil, 2005). Biodiesel is a fuel derived from numerous raw materials such as vegetable oils, animal fats, waste oil, and microalgae. The biodiesel production based on vegetable oils includes feedstocks such as soybean, palm, cotton, peanut, canola, castor, and sunflower. The main fatty materials for biodiesel production are beef tallow, fish oil, and fat of pork and chicken. The most widely known waste oil to produce biodiesel is used cooking oil from domestic and industrial kitchens. And, *Botryococcus braunii*, *Nitzschia sp.*, and *Schizochytrium sp.* are examples of microalgae for biodiesel production (Cremonese et al., 2015; Oliveira; Coelho, 2017).

Brazil presents edaphoclimatic diversity, enabling to cultivate different crops for biodiesel production as soybean, peanut, palm, babassu, canola, sunflower, and jatropha. The soybean presents low oil content (18%) if compared to babassu (66%), palm (55%), and peanut (44-56%). However, despite the potential of other raw materials in Brazil, soybeans are the main feedstock utilized to obtain biodiesel in the country. The soybean crushing process in biodiesel mills generates soybean meal (bran), a by-product that is exported or used as animal feed in the domestic market, and glycerin, a co-product employed in the cosmetics industry (Castanheira et al., 2014; Cremonese et al., 2015).

Brazil is one of the biggest producers and exporters of soybean, the country present adequate productivity, meaning a responsible supply of food, feed, and biofuel. According to CONAB (2019), the Brazilian soybean production in harvest 2005/2006 was 55.03 Million tons (Mtons), increasing to 115.03 Mtons in harvest 2018/2019, a growth of 109.04%, while the planted area expanded 57.70%. As reported by FAO (2019), in the period between 2005 and 2017, the United States was the major exporter of soybean with 528.79 Mtons, and Brazil was the second main exporter with 481.26 Mtons. In 2017, Brazil was the largest player in the international market of soybean, exporting 68.15 Mtons, while the United States was the second exporter with 55.38 Mtons.

According to EIA (2019), Brazil is the second main producer of biodiesel in the world. In 2016, the country supplied 3.24 Million tons of oil equivalent (Mtoe) of biodiesel, while the United States was the major producer with 5.04 Mtoe. In the same year, Indonesia (3.11 Mtoe) and Germany (3.08 Mtoe) were in the second and third positions, respectively. In 2006, at the

beginning of PNPB, Brazil produced 0.06 Mtoe of biodiesel, being placed in the 14th position, Germany was the leading producer (2.28 Mtoe) and the United States (0.81 Mtoe) the second player.

The effects of biodiesel consumption on food supply and prices are a source of concern since soybeans are used as the main raw material for biodiesel production in Brazil. But biodiesel price can be affected by soybean price and the price of derivatives as soybean meal and soybean oil, that is, prices of products of soybean complex (César et al., 2013; Cremonez et al., 2015; Rico; Sauer, 2015). Additionally, the price of biodiesel can suffer influence from the diesel market because the PNPB policy created a blending mandate of biodiesel and petroleum diesel nationwide (Brazil, 2005; Rico; Sauer, 2015). Furthermore, the relationships of petroleum diesel and biodiesel prices are reciprocal since it is needed to use blended diesel in tractors and transportation in crop production.

Biodiesel production and consumption in Brazil are related to several factors such as government policy; markets of food and feed; fossil fuel markets; the environmental agenda as the GHG emissions, the effects on biodiversity, and quality of soil and water; and social impacts on family farming in different regions in the country. Several authors assessed the biodiesel case in Brazil stressing the production process; the historical evolution and perspectives; the main raw materials used and potentialities; the market structure; and the environmental impacts such as in Pousa et al. (2007); Nogueira (2011); Padula et al. (2012); César et al. (2013); Silva Junior (2013); Castanheira et al. (2014); Cremonez et al. (2015); Rico and Sauer (2015); Cerri et al. (2017); César et al. (2017); Moreno-Pérez et al. (2017); Oliveira and Coelho (2017); Miranda et al. (2018); Ribeiro et al. (2018); César et al. (2019); and Oliveira et al. (2019). However, a price analysis concerning the main products of the soybean complex and the relationships with the prices of petroleum diesel and blended diesel are gaps in the literature. Thus, this paper intends to answer the following research questions: What are the effects of the prices of products of the soybean complex on biodiesel prices in Brazil? Are there long-run and short-run influences of soybean price on the price of blended diesel in Brazil? What are the long-run and short-run impacts of biodiesel price on the price of blended diesel in Brazil due to the new blend mandate? Does the Brazilian demand for blended diesel increase with the growth of the income in the short-run and long-run?

This paper aims to investigate the connections between the Brazilian markets of products of the soybean complex, petroleum diesel, and blended diesel through price analysis, highlighting the new relationships due to the biofuel blend mandate. There are three specific objectives: a) to evaluate the existence of short-run and long-run relationships between prices of products of the

soybean complex such as soybean grains, soybean meal, soybean oil, and biodiesel in Brazil; b) to measure the effects of several soybean prices on biodiesel price and, consequently, on price and quantity of blended diesel (diesel C) in the country; and c) to assess the demand for blended diesel in Brazil. For these purposes, we employ time series econometrics techniques focusing on unrestricted and structural specifications of Vector Error Correction Models (VECMs).

3.2. Biodiesel in Brazil

In the 1920s, the National Institute of Technology (INT) carried out initial researches regarding biodiesel in Brazil (Oliveira; Coelho, 2017). However, the existing technology, the insufficient feedstocks, and economic viability were factors that lead this industry to unexpressive development for many years (Rico; Sauer, 2015).

The oil shocks in the 1970s and 1980s resulted in important fuel policies in Brazil: a) in 1975, the creation of Proálcool Program intended to boost the ethanol industry for fuel production; b) in 1976, there was the establishment of mass production of ethanol-powered automobiles through an agreement between the government and the National Association of Automakers (AFAVEA); c) primary studies and programs aiming to use vegetable oil as fuel by National Institute of Technology (INT) (1970), the Plan for the Production of Vegetable Oils for Energy Purposes (1975), which was renamed to Program for the Production of Vegetable Oils for Energy Purposes (1979), Proóleo (1980), and Dendiesel program (1984) (Rico; Sauer, 2015); and d) in 1986, the Research and Development (R&D) on offshore oil production was initiated by Petrobras with the Deep-Water System Technological Innovation Program (PROCAP) (Leite, 2005; Ortiz Neto; Costa, 2007). All these initiatives aimed to substitute imports of crude oil and its derivatives since Brazil was a net importer.

The successful Brazilian experience of biofuel production started in the 1970s with the Proálcool Program, where the government fostered the use of ethanol obtained from sugarcane in vehicles as a way to substitute imports of fossil fuels, mainly crude oil and its derivatives (Moraes; Zilberman, 2014). The ethanol industry contributes to decreasing the dependence on fossil fuels, but also to reduce emissions of GHG. The evolution of this industry, the environmental benefits, and the relationships with food and fossil fuel sectors, usually sugar and gasoline markets in Brazil, were stressed by the Brazilian and international literature from different ways such as in Alves and Bueno (2003); Silva et al. (2009); Figueira et al. (2010); Beiral et al. (2013); Salvo and Huse (2013); Nuñez et al. (2013); Moraes and Zilberman (2014); Khanna et al. (2016); Rodrigues and Bacchi (2016); and Rodrigues and Bacchi (2017). Currently, there is

an obligatory blend of 27% of anhydrous ethanol in pure gasoline, and the existence of hydrous ethanol consumption because of the increasing demand of flex-fuel automobiles and motorcycles, new engines that can run with gasohol (pure gasoline blended with anhydrous ethanol), hydrous ethanol, or a mix of both fuels. The sugarcane price is a crucial component of the anhydrous and hydrous ethanol prices. The anhydrous ethanol price can affect the gasohol price, and the domestic and international sugar prices since Brazil is an important exporter (Khanna et al., 2016).

However, in Brazil, the outcomes regarding biodiesel policies did not present great results if compared to that observed in the sugarcane ethanol industry. The Program for the Production of Vegetable Oils for Energy Purposes (1979) aimed to increase the vegetable oil production, forming a national reserve and exporting this excess or using it as a substitute for diesel. Between 1981 and 1985, the National Program of Renewable Energy of Vegetable Origin was implemented by the Department of Industrial Technology of the Ministry of Development, Industry, and Trade (STI/MDIC) and, in 1982, the National Energy Program of Vegetable Oil was launched as part of this initiative (Rico; Sauer, 2015). Nevertheless, as the increase of crude oil prices contributed to biodiesel research in Brazil in the 1970s, the drop in fossil fuel prices in the middle of the 1980s discouraged the development of the biodiesel sector. These programs were established targeting to produce fuel from vegetable oils, but the main problem was the economic viability of biodiesel if compared to petroleum diesel prices.

Due to environmental concerns on climate change caused by GHG emissions, some countries from Latin America started to introduce blending mandates of fossil fuels and biofuels such as Paraguay (1999), Colombia (2001), Costa Rica (2003), Guatemala (2003), Peru (2003), Ecuador (2004), Argentina (2006), Uruguay (2007), and Chile (2008) (César et al., 2013; Rico; Sauer, 2015). Following the international agenda, in 2002, with Decree No. 702, the Brazilian government established the Probiodiesel, an initiative of the Ministry of Science and Technology for production and consumption of biodiesel. From this effort, it was created an Inter-Ministry working group to discuss the development of the biodiesel sector (Rico; Sauer, 2015; Oliveira; Coelho, 2017). In 2004, the Brazilian government launched the National Biodiesel Production and Use Program (PNPB), a policy aiming to boost biodiesel production and consumption in a sustainable way. The specific objectives of PNPB are to reduce diesel imports through renewable energy, the diversification of energy matrix, social inclusion, and regional development. The program has economic, social, and environmental purposes, and it was consolidated through Law No. 11,097 (Brazil, 2005; Rico; Sauer, 2015; Moreno-Pérez et al., 2017).

The PNPB determines the blending mandate policy of biodiesel in pure petroleum diesel in Brazil. In the beginning, the blend was voluntary, being 2% of biodiesel into petroleum diesel, but in January 2008, the mixture began to be obligatory, increasing to 3% in July 2008. The blend mandate experienced adjustments, growing all over the years: Jul. 2004, 4%; Jan. 2010, 5%; Aug. 2014, 6%; Nov. 2014, 7%; and Mar. 2018, 10% (Brazil, 2005; ANP, 2019).

With PNPB, there is a reduction of federal taxes such as PIS/PASEP¹² and COFINS¹³ for biodiesel producers, aiming to diversify the raw materials used to produce biodiesel in locations that are traditionally poor in the country. There are tax incentives for crushers that use alternative feedstocks such as palm and castor oil in North, Northeast, and Semi-arid regions, since these crops are important to support the territorial inclusion through small scale production systems, mainly in the Amazonian area (Moreno-Pérez et al., 2017). Besides that, the government added as an instrument the Social Fuel Stamp (SFS), a certification granted to biodiesel producers that purchase raw materials from family farmers and provide technical assistance.

The PNPB presents ambivalent results because the program succeeded in increasing biodiesel production but failed in the feedstock diversification and territorial inclusion, since a significant share of biodiesel in Brazil is obtained from soybeans planted in the Central-West and South regions (Moreno-Pérez et al., 2017). According to Rico and Sauer (2015), soybeans and beef tallow are the main feedstocks for biodiesel production, both belonging to important segments of agribusiness in Brazil. The called second-generation biofuels are characterized by using raw materials that do not compete with food markets. Animal fat and microalgae are the main examples. Concerning the fatty material, fat of swine and chicken, and beef tallow are important feedstocks, since Brazil is a significant producer and exporter of cattle, chicken, and pork. The wastes from these processing industries are considerable sources for biodiesel production due to the low cost (Cremonez et al., 2015). In 2017, Brazil was the main exporter of cattle meat (boneless, beef, and veal) with 1.19 Mtons and chicken meat with 3.94 Mtons. Besides that, the country was the fifth main exporter of pork meat with 0.56 Mtons (FAO, 2019). The microalgae present a strong potential for biodiesel production, but the industrial costs are high (Cremonez et al., 2015). Figure 4 shows the raw materials used by biodiesel mills in Brazil. In 2008, soybeans represented 68.66% of the total feedstock used to obtain biodiesel, followed by animal fats (17.73%). In 2018, the soybean's share was 66.92%, and animal fats achieved 15.54%.

¹² Program of Social Integration (PIS) and Program of Patrimony Formation of Public Servants (PASEP) refer to contributions from legal entities.

¹³ Contribution to the Social Security Funding (COFINS) is collected from enterprises' gross revenue.

Figure 4. Feedstocks used in biodiesel production in Brazil (2008 - 2018)

Source: prepared by the authors with data from ANP (2019), and ABIOVE (2019).

The feedstock is a critical factor in biodiesel production. In Brazil, soybean cultivation is based on monoculture plantations and technology, meaning smaller raw material costs for biodiesel producers. There are several advantages of using soybeans to produce biodiesel in the country: a) quality of the product; b) adequate quantity to sustain the demand of biodiesel; c) low costs of transportation, storage, and crushing if compared to other oilseeds; d) research and development in soybean production; e) it generates by-products that can be commercialized such as soybean meal; and, f) there is a set of cooperatives and companies that contributes to the sector strength. Animal fat is another important source for biodiesel producers. Since Brazil is an important meat producer and exporter, the processing meat industry generates a significant amount of fatty materials, being these cheaper if compared to vegetable oils (Castanheira et al., 2014; Moreno-Pérez et al., 2017). According to Castanheira et al. (2014), beef tallow is an important co-product of the meat industry because slaughterhouses and retailers generate approximately 15 kg of usable fatty material per cattle.

The biodiesel presents fewer emissions of greenhouse gases if compared to petroleum diesel. But, the impacts on biodiversity and biota losses are still uncertain since the use of arable land to produce energy crops can affect soil quality (César et al., 2013). The use of petroleum derivatives as inputs in the fertilizer production, in the harvesting stage, and transportation are factors that result in a certain level of GHG emissions (Cremonez et al., 2015). According to Nogueira (2011), in Brazil, the soybean cultivation, that is, the feedstock production level of biodiesel, generates 685.2 g CO₂eq/kg of biodiesel, and the processing stage contributes with 426.1 g CO₂eq/kg of biodiesel, totaling 1111.3 g CO₂eq/kg of biodiesel in the life cycle. The biodiesel from beef tallow releases 512.0 g CO₂eq/kg of biodiesel in the life cycle. Thus, if

compared to petroleum diesel, the biodiesel from these raw materials presents mitigation effects, a reduction of 62% and 82% of GHG emissions, respectively. According to Castanheira et al. (2014), the land-use change (LUC) and the life cycle assessment (LCA) are important elements for the biodiesel industry. The use of land as an input for energy production can generate impacts on biodiversity, ecological soil quality, and biotic production potential, as well as the growth of GHG emissions if crop cultivation is based on less developed techniques of farm management, archaic mechanization, application of fertilizers and chemicals, and the use of fossil fuels in equipment and crop transportation. According to Miranda et al. (2018), there is criticism from the literature of using vegetable oil for biodiesel production, the increasing demand for biofuels can lead to an expansion of farming, transforming, directly and indirectly, native forest fragments in land for agricultural purposes.

Other raw materials, as palm and castor oil, present industrial applications that can generate more added value. For example, castor oil can be used in the pharmaceutical industry and palm oil in the food sector, as a consequence, their utilization in biodiesel production is not expressive in Brazil (Rico; Sauer, 2015; Moreno-Pérez et al., 2017). Used cooking oil can be one important source. Residences, commerce, and the industry produce an enormous amount of cooking oil waste. One liter of cooking oil can pollute 20 thousand liters of water if discarded irregularly, but the collection cost and the logistics for transportation can be the main factors discouraging biodiesel producers from using this type of raw material (Miranda et al., 2018). Therefore, the Brazilian biodiesel production is significantly based on soybeans. Figure 5 presents the Brazilian states with the largest soybean and biodiesel production.

As shown in Figure 5a, in harvest 2007/2008, the main soybean producer states were Mato Grosso with 17.85 Mtons, accounting to 29.74% of the Brazilian production, Paraná with 11.90 Mtons (19.82%), and the Rio Grande do Sul with 7.78 Mtons (12.95%). In harvest 2017/2018, the same states were the biggest producers (Figure 5b), Mato Grosso (32.31 Mtons, 27.08%), Paraná (19.17 Mtons, 16.07%), and the Rio Grande do Sul (17.15 Mtons, 14.38%). These states present a large planted area and adequate productivity (ton/ha). For example, in harvest 2017/2018, Mato Grosso's planted area was 9.52 Million ha with productivity equals to 3.39 ton/ha (in Appendix D, Tables D1 and D2 show the values for all Brazilian states).

According to Figure 5c, the largest biodiesel producers in 2008 were the Rio Grande do Sul with 306.06 Thousand m^3 (Mm^3), which represented 27.79% of the Brazilian production, Mato Grosso (25.87%), and Goiás (21.19%). In 2018, Rio Grande do Sul was the major biodiesel producer, exhibiting a share of 29.74% with approximately 1.5 Million m^3 (MMm^3), Mato Grosso

(22.79%) was in the second position followed by Goiás (15.23%). Thus, the main soybean producers became key biodiesel supplier states in Brazil in the last years.

Figure 5. Brazilian production of soybeans and biodiesel

Source: prepared by the authors with data from CONAB (2019), ANP (2019), and software QGIS 3.6.3.

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

Regarding the market structure, Moreno-Pérez et al. (2017) highlight that the market concentration suffered important changes in the biodiesel industry. In 2005, the Concentration

Ratio (CR_4)¹⁴ for the four main firms in the market was 100%, that is, few companies were responsible for all biodiesel supply in Brazil, while the Herfindahl Hirschman Index (HHI)¹⁵ was 0.383. In 2016, the CR_4 was 39%, and the HHI was 0.067. The biodiesel sector was concentrated in 2005, becoming deconcentrated as the blending share of biodiesel in petroleum diesel started to expand. The entrant firms in the biodiesel market are soybean oil producers that added the biodiesel stage in the crushing plant or rented the processing installations from other mills. In 2016, the Brazilian firms could be classified by their output: biodiesel (8 plants); biodiesel and foodstuff (20 plants); and, biodiesel and non-foodstuff (6 plants) (Moreno-Pérez et al., 2017).

The biodiesel market works through auctions. Until the 26th auction, Petrobras was the main buyer of biodiesel from mills, re-auctioning this biofuel with authorized distributors in the market. Starting in the 26th auction, the biodiesel producers could sell directly to distributors. The National Agency of Petroleum, Natural Gas, and Biofuel (ANP) has an important role in this framework, the agency supervises and regulates the commercialization. The market price of biodiesel is set in auctions overseen by ANP, considering a maximum reference price of biodiesel based on the main feedstocks used in production (Rico; Sauer, 2015; ANP, 2019). The price of biodiesel is higher than the price of domestic soybean oil, even without including the transportation costs to the blending locations (Rico; Sauer, 2015). As the Brazilian biodiesel demand arose from blend mandate policy, the quantity produced and consumed follow the same trend, since this fuel is used as complementary to petroleum diesel (Cremonese et al., 2015; EPE, 2019). Figure 6a presents the prices of biodiesel, soybean oil, petroleum diesel at refineries, and blended diesel at the pump.

In Figure 6a, between January 2006 and December 2018, the price of biodiesel was typically higher than the price of petroleum diesel. The average price of biodiesel was R\$ 3.19 per liter, while the price of petroleum diesel was R\$ 2.35 per liter, and the price of blended diesel was R\$ 3.03 per liter. In some periods, the price of soybean oil was higher than the biodiesel price, leading crushers to prefer the first one. Figure 6b shows the quantity of biodiesel, pure diesel, and blended diesel consumed in Brazil. The monthly average consumption of biodiesel was 0.23 Billion liters, and petroleum diesel was 4.33 Billion liters. The level of biodiesel consumption increased surprisingly 45,230.94% if compared values of January 2006 and December 2018, while the pure diesel consumption grew up 5.94%.

¹⁴ $CR_k = \sum_{i=1}^k S_i$, where CR_k is the Concentration Ratio of k -largest firms, and S_i is the market share of each firm i (Church; Ware, 2000).

¹⁵ $HHI = \sum_{i=1}^N S_i^2$, where S_i is the share (in percentage) of each firm in the industry: if $HHI < 0.15$, the industry is deconcentrated; if $0.15 \leq HHI < 0.25$, the industry is averagely concentrated; and if $HHI > 0.25$, the industry is concentrated (Church; Ware, 2000; U.S. Department of Justice; Federal Trade Commission, 2010).

Figure 6. Prices and quantity regarding diesel and biodiesel markets in Brazil (Jan. 2006 - Dec. 2018)

Source: prepared by the authors with data from ANP (2019), CONAB (2019), FGV (2019), and software RStudio 1.2.1578.

Note: prices in Reais (R\$) of December 2018, the Brazilian currency.

3.3. Methodology

3.3.1. Time series econometrics approach

We use the time series econometrics approach to evaluate three important topics in Brazil: A) the relationships between prices of products of the soybean complex such as soybean grains, soybean meal, soybean oil, and biodiesel; B) the linkages between diesel, biodiesel, and soybean markets; and, C) the demand of blended diesel.

To evaluate the stationarity of the time series, we employ the Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) unit root test, including trend or constant. The null hypothesis is that

the time series is stationary ($H_0: y_t \sim I(0)$) against the alternative that the time series is non-stationary ($H_1: y_t \sim I(1)$) (Kwiatkowski et al., 1992; Pfaff, 2008; Bueno, 2011). Additionally, we use the Dickey-Fuller Generalized Least Squares (DF-GLS) test with the null hypothesis of non-stationarity of the time series ($H_0: y_t \sim I(1)$) against the stationarity ($H_1: y_t \sim I(0)$) (Elliott et al., 1996; Pfaff, 2008).

Knowing the integration order of each time series, we apply the Granger-causality analysis to highlight some important relations from data. The Granger-causality test assesses if a time series y_{1t} is important to forecast another variable y_{2t} . The null hypothesis is that y_{1t} does not Granger-cause y_{2t} , against the alternative that y_{1t} Granger-causes y_{2t} (Granger, 1969; Lütkepohl; Krätzig, 2004). Lütkepohl and Krätzig (2004) emphasize that it is important to observe if there is Granger-causality from both directions, that is, to test if y_{2t} does not Granger-cause y_{1t} and if y_{1t} does not Granger-cause y_{2t} to remove all significant information for modeling. However, to evaluate all combinations for a model with several variables can be puzzling and lead to some relations without economic meaning. According to Bueno (2011), the Granger-causality analysis includes past and current values of y_{1t} on y_{2t} and must be carried out using stationary time series in level or the first difference. Lütkepohl and Krätzig (2004) highlight that if there is cointegration between two variables, there must also be Granger-causality at least in one direction, despite these approaches investigate data from different aspects.

The next step is to determine the lag order for a set of variables based on an unrestricted Vector Autoregression (VAR) model with order $m = 0, \dots, p_{max}$. The order for an unrestricted VAR model is chosen considering the number of lags that minimizes the information criterion, the Akaike Information Criterion ($AIC(p)$) in our study. But, if all variables are $I(1)$, a VAR model is not an adequate specification, a Vector Error Correction Model (VECM) is appropriate. A VECM is based on the concept of cointegration, which means a linear combination among $I(d)$ time series resulting in a variable that presents lower order of integration (Engle; Granger, 1987; Pfaff, 2008). The time series of one vector y_t are cointegrated if all variables of y_t are $I(d)$ and if exists a cointegrating vector different from zero. From this concept, it is possible to evaluate a long-run relationship between non-stationary time series.

Considering the system y_t , the cointegration is based on the rank ($rk = r$) of a matrix $\Pi = \alpha\beta'$, since Π is a matrix $K \times K$, and α and β are matrices $K \times r$, where $\alpha\beta'y_{t-p}$ and $\beta'y_{t-p}$ are both stationary. Thus, if: (i) $rk(\Pi) = K$, there are K linearly independent combinations of time series in the system y_t ; (ii) $rk(\Pi) = 0$, there is no linear combination that turns Πy_t stationary; and (iii) $0 < rk(\Pi) = r < K$, there is no full rank, resulting in $\Pi = \alpha\beta'$, where there are r linear

independent columns in β , the cointegrating vector (a long-run relationship), and exists α , a vector that determines the speed of adjustment to the long-run equilibrium (loading matrix) (Pfaff, 2008; Enders, 2010).

To evaluate the cointegration of time series, we apply Trace and Maximum Eigenvalue tests (Johansen, 1988; Johansen; Juselius, 1990), both based on constrained estimates using maximum likelihood. Trace test assumes that the rank of Π is equal to the number of characteristics roots (eigenvalues) different from zero (Enders, 2010; Bueno, 2011). Therefore, Trace tests sequentially the following hypotheses (Bueno, 2011):

$$H_0(0): rk(\Pi) = 0 \quad \times \quad H_1(0): rk(\Pi) > 0 \quad (17)$$

$$H_0(1): rk(\Pi) = 1 \quad \times \quad H_1(1): rk(\Pi) > 1 \quad (18)$$

$$\vdots$$

$$H_0(K-1): rk(\Pi) = K-1 \quad \times \quad H_1(K-1): rk(\Pi) = K \quad (19)$$

The Maximum Eigenvalue test evaluates the highest eigenvalue that results in a cointegrating vector. It sequentially tests the following hypotheses (Lütkepohl; Krätzig, 2004; Bueno, 2011):

$$H_0(0): rk(\Pi) = 0 \quad \times \quad H_1(0): rk(\Pi) = r+1 \quad (20)$$

$$H_0(1): rk(\Pi) = 1 \quad \times \quad H_1(1): rk(\Pi) = r+1 = 2 \quad (21)$$

$$\vdots$$

$$H_0(K-1): rk(\Pi) = K-1 \quad \times \quad H_1(K-1): rk(\Pi) = K \quad (22)$$

After the preliminary tests, we evaluate the best specification to fit our models, VARs or VECMs, and compute the diagnostics. The next section describes the rationale of these approaches.

3.3.2. SVARs and SVECMs

According to Lütkepohl and Krätzig (2004), the Vector Autoregression (VAR) model is a class of data generation process to evaluate time series for a specific period assuming that all variables are endogenous. However, economic theory can be an important source to impose restrictions. In several cases, variables present a common stochastic trend, a link between time series that can be explained by economic models. It is important to highlight that if there is a

common stochastic trend, the variables are called cointegrated (Granger, 1981; Eagle; Granger, 1987). If a set of time series for a VAR model is non-stationary and cointegrated, the VAR specification is not the best way to fit a model. In this case, it is used Vector Error Correction Model (VECM) as an alternative parameterization. As presented by Pfaff (2008), a VAR model of order p is specified as:

$$y_t = A_1 y_{t-1} + \dots + A_p y_{t-p} + C D_t + u_t \quad (23)$$

where, $y_t = (y_{1t}, \dots, y_{kt}, \dots, y_{Kt})'$ is a set of K endogenous variables, which $k = 1, \dots, K$; A_i 's $= (K \times K)$, coefficient matrices considering $i = 1, \dots, p$; C = coefficient matrix of deterministic regressors with dimension $K \times M$; D = column vector $(M \times 1)$ of deterministic regressors such as trend, constant, seasonal dummies, and other specific dummies; and $u_t = (u_{1t}, \dots, u_{Kt})'$, is a white noise process, that is, the unobservable error term with zero-mean, time-invariant positive definite covariance matrix $E(u_t u_t') = \Sigma u$, where u 's are stochastic vectors with $u_t \sim (0, \Sigma u)$. This process is stable if it generates stationary time series with time-invariant means, variances, and covariances, which can be checked using the polynomial $\det(I_k - A_1 z - \dots - A_p z^p) \neq 0$ for $|z| \leq 1$. If $z = 1$, the time series are integrated of order one, $I(1)$ (Pfaff, 2008). If variables are $I(1)$, the VECM model is a suitable specification. The VECM $(p - 1)$ is given by (Lütkepohl; Krätzig, 2004):

$$\Delta y_t = \Pi y_{t-1} + \Gamma_1 \Delta y_{t-1} + \dots + \Gamma_{p-1} \Delta y_{t-p+1} + C D_t + u_t \quad (24)$$

where, $\Pi = -(I_k - A_1 - \dots - A_p)$; and $\Gamma_i = -(A_{i+1} + \dots + A_p)$, with $i = 1, \dots, p - 1$. The VECM assumes the differences of the variables $\Delta y_t = y_t - y_{t-1}$. Πy_{t-1} contains the cointegrating relations and it is called the long-run term, while Γ_i 's are short-run terms. A VAR process in the presence of unit roots implies that $\det(I_k - A_1 z - \dots - A_p z^p) = 0$ for $z = 1$, so $\Pi = -(I_k - A_1 - \dots - A_p)$ is singular. Let $\Pi = \alpha \beta'$ be the product of $(K \times r)$ matrices α and β with $\text{rank}(\alpha) = \text{rank}(\beta) = r$, thus $\text{rank}(\Pi) = r$. Therefore, there is a cointegrating relation among series of y_t , β is a cointegrating matrix, and α is the loading matrix, which represents the weights regarding the cointegrating relations for each equation in the VECM (Lütkepohl; Krätzig, 2004; Enders, 2010).

VAR and VECM specifications must comprise economic theory on modeling. Some coefficients often do not present a theoretical foundation to ensure inclusion in the model. As a result, the coefficient estimates by unrestricted VARs or VECMs can lead to cases where it is difficult to draw some explanation, so it is necessary to impose an economic meaning on the econometric model. This methodological concern is known as Lucas's critique (Lütkepohl; Krätzig, 2004). A new class of model was established to solve this problem, the Structural Vector Autoregression (SVAR), where the ordering of the variables matters, and it is possible to include restrictions on equations considering economic theory. A generic SVAR model is given by:

$$Ay_t = A_1^*y_{t-1} + \dots + A_p^*y_{t-p} + CD_t + B\varepsilon_t \quad (25)$$

where, A = matrix $K \times K$ that enables to model instantaneous relationships among time series of y_t ; and $\varepsilon_t \sim (0, I_k)$. Structural shocks are important in the SVARs and SVECMs, the structural innovations (ε_t) are related to the residues through a linear relation $B\varepsilon_t$, since B is $K \times K$. The SVECM is given by:

$$A\Delta y_t = \Pi^*y_{t-1} + \Gamma_1^*\Delta y_{t-1} + \dots + \Gamma_{p-1}^*\Delta y_{t-p+1} + CD_t + B\varepsilon_t \quad (26)$$

We check our models through several diagnostic tests. The Portmanteau statistic (Q_h) is an important tool to verify residual autocorrelation, which the null hypothesis is that $H_0: E(u_t u'_{t-i}) = 0$ with $i = 1, \dots, h > p$ against $H_1: E(u_t u'_{t-i}) \neq 0$ for some i , that is, the alternative establishes that at least one autocorrelation is different from zero considering h lags (Lütkepohl; Krätzig, 2004; Enders, 2010). We employ multivariate Jarque-Bera (JB) (1987) test to check the normality of residues, which null hypothesis is that residues are normal against the alternative of non-normality (Bueno, 2011). For heteroscedasticity, we use the Multivariate ARCH-LM test (MARCH-LM), where the null hypothesis is that there is no heteroscedasticity against the alternative of the presence of it (Lütkepohl; Krätzig, 2004; Bueno, 2011). Finally, we check deviations from parameter constancy, that is, structural stability, through the OLS-CUSUM test (Lütkepohl; Krätzig, 2004; Pfaff, 2008).

3.3.3. Data

We selected time series regarding diesel market, soybean complex, and income in Brazil from several sources. The monthly data ranges from January 2006 to December 2018, totaling 156 observations. Table 12 summarizes the selected variables for our models.

Table 12. Selected variables

Variable	Description	Source
<i>Pda</i>	Price of diesel A (pure) at the refinery level (R\$/liter)	ANP(2019)
<i>Pbio</i>	Price of biodiesel at the auction level (R\$/liter)	ANP(2019)
<i>Pdc</i>	Price of diesel C (pure diesel blended with biodiesel) at the pump level (R\$/liter)	ANP(2019)
<i>Qda</i>	Quantity of diesel A (pure petroleum diesel) (liters)	ANP(2019)
<i>Qbio</i>	Quantity of biodiesel (liters)	ANP(2019)
<i>Qdc</i>	Quantity of blended diesel (diesel C) (liters)	ANP (2019)
<i>Gdp</i>	Gross Domestic Product (GDP) (Million R\$)	BCB (2019)
<i>Psoy_{x,PR}</i>	Soybean price at Paranaguá Port, Paraná State (FOB - R\$/bag of 60 kg)	ABIOVE (2019)
<i>Psoy_{d,PR}</i>	Soybean price at Maringá, Paraná State (R\$/bag of 60 kg)	ABIOVE (2019)
<i>Psoy_{d,SP}</i>	Soybean price at Mogiana, São Paulo State (R\$/bag of 60 kg)	ABIOVE (2019)
<i>Psoy_{d,RS}</i>	Soybean price at Passo Fundo, Rio Grande do Sul State (R\$/bag of 60 kg)	ABIOVE (2019)
<i>Psoy_{d,MT}</i>	Soybean price at Rondonópolis, Mato Grosso State (R\$/bag of 60 kg)	ABIOVE (2019)
<i>Pmeal_{d,SP}</i>	Soybean meal price at São Paulo State (R\$/bag of 60 kg)	ABIOVE (2019)
<i>Psoyoil_{d,SP}</i>	Soybean oil price at São Paulo State (R\$/liter)	ABIOVE (2019)

Source: prepared by the authors.

The Brazilian price of biodiesel (*Pbio*) was obtained from the Brazilian Association of Vegetable Oil Industries (ABIOVE, 2019), which is determined in auctions. The price of pure petroleum diesel (diesel A) at the refinery level (*Pda*) and blended diesel (diesel C) at the pump level (*Pdc*) were obtained from the National Agency of Petroleum, Natural Gas, and Biofuels (ANP, 2019). The price of diesel C at the pump level considers the blend mandate of biodiesel in pure diesel, taxes applied by the government, freight costs, and margins from dealers, being measured in Reais (R\$), the Brazilian currency, per liter (R\$/liter). The quantity of pure diesel consumption (*Qda*) is given by the summation of Brazilian production and imports minus the exports of diesel. Therefore, the quantity of diesel C (*Qdc*) is given by the summation of biodiesel (*Qbio*) and diesel (*Qda*). The volumes of *Qbio*, *Qda*, and *Qdc* are expressed in liters. These time series were collected in ANP (2019).

We collected soybean prices from ABIOVE (2019), choosing different locations in Brazil and two destinations, domestic market (*d*) or exports (*x*): *Psoy_{x,PR}*, Paranaguá Port at Paraná State (PR); *Psoy_{d,PR}*, Maringá (PR); *Psoy_{d,SP}*, Mogiana at São Paulo State (SP); *Psoy_{d,RS}*, Passo Fundo at the Rio Grande do Sul State (RS); and *Psoy_{d,MT}*, Rondonópolis at Mato Grosso State (MT). These prices are measured in R\$ per bag of 60 kg. Additionally, we selected the prices of two important products of soybean complex, the soybean meal price (*Pmeal_{d,SP}*) in R\$ per bag

of 60 kg and the soybean oil price ($P_{soyoil_{d,SP}}$) in R\$/liter, both at the crushing level in São Paulo State.

The locations concerning prices of products from soybean complex were chosen because of their expressiveness in soybean and biodiesel production, and due to data availability. We chose monthly data of the Brazilian Gross Domestic Product (Gdp) as a proxy of income, which was obtained from the Brazilian Central Bank (BCB, 2019). The data regarding fossil fuel prices, price of products of soybean complex (soybean grains, soybean meal, soybean oil, and biodiesel), and GDP were deflated using the General Price Index - Domestic Availability (IGP-DI) from Fundação Getúlio Vargas (FGV, 2019). The prices are in Reais (Brazilian currency, R\$) of December 2018. Moreover, we applied the natural logarithm in all series to reduce the difference of scale between them and directly obtain the elasticities. Table 13 presents the descriptive statistics. In Appendix C, Figures C1, C2, and C3 show the time series used in this study.

Table 13. Descriptive statistics (natural logarithm)

Variable	Min.	Max.	Range	Mean	S. E.	Var.	Std. Dev	Coef. Var
Pda	0.684	1.050	0.366	0.851	0.008	0.011	0.104	0.123
$Pbio$	0.827	1.545	0.719	1.143	0.015	0.036	0.191	0.167
Pdc	1.084	1.380	0.296	1.220	0.006	0.006	0.078	0.064
Qda	21.851	22.483	0.632	22.167	0.011	0.018	0.135	0.006
$Qbio$	13.858	20.031	6.173	18.812	0.103	1.654	1.286	0.068
Qdc	21.856	22.541	0.685	22.216	0.012	0.023	0.151	0.007
Gdp	12.831	13.379	0.547	13.193	0.011	0.018	0.132	0.010
$P_{soy_{x,PR}}$	4.096	4.821	0.724	4.418	0.011	0.020	0.143	0.032
$P_{soy_{d,PR}}$	3.956	4.748	0.792	4.333	0.013	0.026	0.161	0.037
$P_{soy_{d,SP}}$	3.885	4.701	0.816	4.312	0.013	0.025	0.159	0.037
$P_{soy_{d,RS}}$	3.889	4.724	0.835	4.344	0.014	0.029	0.170	0.039
$P_{soy_{d,MT}}$	3.700	4.678	0.977	4.246	0.015	0.035	0.187	0.044
$P_{meal_{d,SP}}$	6.568	7.464	0.896	7.014	0.017	0.047	0.216	0.031
$P_{soyoil_{d,SP}}$	0.747	1.585	0.838	1.094	0.013	0.027	0.165	0.151

Source: prepared by the authors with RStudio 1.2.1578.

3.3.4. Econometric specifications

Since this paper aims to investigate the relationships between prices of soybean complex products, price of diesel, and the demand for blended diesel in Brazil, we propose three frameworks. First, the Brazilian biodiesel price ($Pbio$) is affected by:

$$Pbio = f(P_{soyoil_{i,j}}, P_{meal_{i,j}}, P_{soy_{i,j}}) \quad (27)$$

where, $P_{soyoil_{i,j}}$ = soybean oil price; $P_{meal_{i,j}}$ = soybean meal price; $P_{soy_{i,j}}$ = soybean price; i = destination, exports (x) or domestic market (d); j = locations (PR, SP, RS, MT); and $P_{soy_{i,j}} = (P_{soy_{x,PR}}, P_{soy_{d,PR}}, P_{soy_{d,SP}}, P_{soy_{d,RS}}, P_{soy_{d,MT}})$. We assume that the Brazilian

biodiesel production is obtained mainly from soybeans, as presented previously. Consequently, the biodiesel price will depend on the prices of soybean complex products. In the unrestricted models for equation (27), the innovations are orthogonalized applying the traditional Choleski's decomposition of the covariance matrix, as specified by Sargent (1978) and Sims (1980). To include some economic meaning on our estimates, we impose restrictions on short-run impact matrix A and long-run impact matrix B in equations (25) or (26), depending on the integration order of selected variables for each model. Our structural forms for soybean complex models assume that $Pbio$ is influenced by $Psoy_{oil,i,j}$, $Pmeal_{i,j}$, and $Psoy_{i,j}$ in the short-run impact matrix A . The other variables are affected by their values. If y_t is the vector of selected time series, thus:

$$y_t = [Pbio, Psoy_{oil,i,j}, Pmeal_{i,j}, Psoy_{i,j}] \quad (28)$$

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & a_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (29)$$

And the restricted long-run impact matrix (B) presupposes that $Pmeal_{i,j}$ does not affect $Psoy_{i,j}$ in the long-run, since soybean meal is a co-product that will depend on the production of soybean oil and biodiesel:

$$B = \begin{bmatrix} 1 & b_{12} & b_{13} & b_{14} \\ b_{21} & 1 & b_{23} & b_{24} \\ b_{31} & b_{32} & 1 & b_{34} \\ b_{41} & b_{42} & 0 & 1 \end{bmatrix} \quad (30)$$

Second, the price of blended diesel (diesel C) is a function of:

$$Pdc = f(Qdc, Pda, Pbio, Psoy_{i,j}) \quad (31)$$

where, Pdc = price of diesel C; Qdc = quantity of diesel C; Pda = price of diesel A, pure diesel; $Pbio$ = price of biodiesel; and $Psoy_{i,j}$ = soybean price from several locations with different destinations. The unrestricted models use Choleski's decomposition of the covariance matrix. The restrictions imposed on the short-run impact matrix (A) regarding the price of diesel C are specified by:

$$y_t = [Pdc, Qdc, Pda, Pbio, Psoy_{i,j}] \quad (32)$$

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & a_{14} & a_{15} \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (33)$$

The restricted long-run impact matrix (B) assumes that the price of pure diesel (Pda) is not affected by soybean price ($Psoy_{i,j}$) and biodiesel price ($Pbio$). Additionally, soybean price does not depend directly on pure diesel price (Pda). $Psoy_{i,j}$ is influenced by the price of blended diesel at the pump level due to the reciprocal effect since blended diesel is used as an input in soybean cultivation, that is, it is a component of soybean production cost. Therefore:

$$B = \begin{bmatrix} 1 & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & 1 & b_{23} & b_{24} & b_{25} \\ b_{31} & b_{32} & 1 & 0 & 0 \\ b_{41} & b_{42} & b_{43} & 1 & b_{45} \\ b_{51} & b_{52} & 0 & b_{54} & 1 \end{bmatrix} \quad (34)$$

Third, the blended diesel demand is given by (35), accounting for the matrices presented in (37) and (38). We keep the long-run impact matrix (B) unrestricted, limiting only the contemporaneous relationships, as proposed by Rodrigues and Bacchi (2016; 2017) for the case of the light fuel demand in Brazil. The blended diesel demand is given by:

$$Qdc = f(Pdc, Gdp) \quad (35)$$

$$y_t = [Qdc, Pdc, Gdp] \quad (36)$$

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (37)$$

$$B = \begin{bmatrix} 1 & b_{12} & b_{13} \\ b_{21} & 1 & b_{23} \\ b_{31} & b_{32} & 1 \end{bmatrix} \quad (38)$$

3.4. Results

3.4.1. Unit Root and Granger-Causality tests

Table 14 shows the results for KPSS and DF-GLS unit root tests. For KPSS, considering the version with a trend, we can see that the non-stationary time series are the price of pure diesel (Pda), price of blended diesel (Pdc), the quantity of blended diesel (Qdc), Gross Domestic Product (Gdp), and soybean price in the Rio Grande do Sul ($Psoy_{d,RS}$) and Mato Grosso ($Psoy_{d,MT}$). All selected time series are non-stationary for the KPSS test with constant.

Table 14. KPSS and DF-GLS unit root tests

Variable	KPSS ^a		DF-GLS ^b	
	Trend statistic	Constant statistic	Trend statistic	Constant statistic
Pda	0.259 ***	0.496 **	-1.603	-0.549
$Pbio$	0.099	1.032 ***	-2.455	-0.360
Pdc	0.275 ***	0.468 **	-1.167	-0.671
Qdc	0.251 ***	0.958 ***	-1.144	0.087
Gdp	0.291 ***	1.007 ***	-0.928	-0.132
$Psoy_{x,PR}$	0.115	0.447 *	-1.933	-0.862
$Psoy_{d,PR}$	0.104	0.475 **	-2.094	-0.992
$Psoy_{d,SP}$	0.108	0.494 **	-1.795	-0.688
$Psoy_{d,RS}$	0.132 *	0.540 **	-1.792	-0.652
$Psoy_{d,MT}$	0.138 *	0.604 **	-1.973	-0.766
$Pmeal_{d,SP}$	0.069	0.517 **	-2.501	-1.770 *
$Psoy_{oil,d,SP}$	0.107	0.387 *	-1.174	-1.073

Source: prepared by the authors with RStudio 1.2.1578.

Note: ^a For KPSS the critical values are from Kwiatkowski et al. (1992) - i) trend: 1% = 0.216, 5% = 0.146, and 10% = 0.119; ii) constant: 1% = 0.739, 5% = 0.463, and 10% = 0.347. 13 lags included.

^b For DF-GLS the critical values are from MacKinnon (1991) - i) trend: 1% = -3.460, 5% = -2.930, and 10% = -2.640; ii) constant: 1% = -2.580, 5% = -1.940, and 10% = -1.620. 13 lags included.

The DF-GLS unit root tests do not reject the null hypothesis of non-stationarity, except for $Pmeal_{d,SP}$ with constant at 10% of significance. Therefore, considering the results of DF-GLS tests, we conclude that the time series for our econometric specifications are $I(1)$ at 5% of significance, being VECM and SVECM the recommended approaches.

We run Granger-causality tests and Cointegration tests. First, the Granger-causality tests are helpful to observe some relationships from data that can be important for VECM and SVECM specifications. Second, the Cointegration tests verify if the selected variables present a long-run relationship for each model proposed.

According to Figure 7, the price of pure diesel (Pda) Granger-causes the price of blended diesel (Pdc), and Pdc Granger-causes Pda . The price of biodiesel ($Pbio$) Granger-causes soybean price at Passo Fundo-RS ($Psoy_{d,RS}$) and soybean meal price at Mogiana-SP ($Psoy_{d,SP}$).

On the other hand, $Pbio$ is caused, in Granger sense, by the price of diesel C, the domestic soybean price at Maringá-PR ($Psoy_{d,PR}$), and Passo Fundo-RS ($Psoy_{d,RS}$). The quantity of diesel C (Qdc) Granger-causes the quantity of diesel A (Qda) and biodiesel ($Qbio$), while Qdc is caused by Qda and $Qbio$, reinforcing the complementarity of fossil fuels and biofuels from blend mandate policy.

The macroeconomic variable included in our analysis as a proxy of income, the Gdp , Granger-causes fuel prices and the quantities such as Pda , Pdc , Qda , $Qbio$, and Qdc . Moreover, Gdp Granger-causes the price of food and feed such as soybean price at Rondonópolis-MT ($Psoy_{d,MT}$) and soybean meal price at São Paulo State ($Pmeal_{d,SP}$).

Variable	ΔPda	$\Delta Pbio$	ΔPdc	ΔQda	$\Delta Qbio$	ΔQdc	ΔGdp	$\Delta Psoy_{x,PR}$	$\Delta Psoy_{d,PR}$	$\Delta Psoy_{d,SP}$	$\Delta Psoy_{d,RS}$	$\Delta Psoy_{d,MT}$	$\Delta Pmeal_{d,SP}$	$\Delta Psoy_{oil_{d,SP}}$
ΔPda			↗				↗							
$\Delta Pbio$			↗						↗		↗			
ΔPdc	↗						↗			↗				
ΔQda					↗	↗	↗							
$\Delta Qbio$				↗		↗	↗		↗		↗			
ΔQdc				↗	↗		↗							
ΔGdp	↗		↗											
$\Delta Psoy_{x,PR}$									↗		↗			
$\Delta Psoy_{d,PR}$					↗			↗			↗			
$\Delta Psoy_{d,SP}$								↗	↗			↗		
$\Delta Psoy_{d,RS}$		↗						↗	↗			↗		
$\Delta Psoy_{d,MT}$				↗		↗	↗	↗						
$\Delta Pmeal_{d,SP}$	↗	↗	↗	↗		↗	↗	↗	↗	↗	↗	↗		
$\Delta Psoy_{oil_{d,SP}}$			↗					↗	↗	↗	↗	↗	↗	

Figure 7. Granger-causality tests

Source: prepared by the authors with RStudio 1.2.1578.

Note: ↗ = Granger-causes.

$Pmeal_{d,SP}$ is Granger-caused by fuel prices (Pda , $Pbio$, and Pdc), the quantity of diesel A and C (Qda , Qdc), the Gdp , and all selected soybean prices. The soybean oil price is Granger-caused by $Psoy_{x,PR}$, $Psoy_{d,PR}$, $Psoy_{d,SP}$, $Psoy_{d,RS}$, $Psoy_{d,MT}$, and $Pmeal_{d,SP}$. The test statistics and p-values can be found in Table D3 (Appendix D). The next three sections present

the results regarding the cointegration rank for each model and the outcomes of VECMs and SVECMs.

3.4.2. Results for soybean complex

Table 15 presents the optimal lags of unrestricted VAR models for the soybean complex, considering a maximum length of 6 lags, AIC as the criterion, and the inclusion of monthly seasonal dummies. All cases indicate 2 lags considering no deterministic regressors or a constant. SB2, SB3, SB4, and SB5 models present 2 lags in the specification with a trend. As the time series included in the models of soybean complex are non-stationary in level, we reject the cases with optimal lag length equals to 1 and test the cointegration rank. For models with $p = 2$, we do not reject the hypothesis that there is at least one cointegrating vector, except for SB4 and SB5 in the Maximum Eigenvalue test with a trend, where we observed no cointegration. Table D7 (Appendix D) shows the critical values and test statistics.

Table 15. Lag-order selection in VAR(p) and cointegration rank (r) for soybean complex models

Variables	Models				
	SB1	SB2	SB3	SB4	SB5
<i>Pbio</i>	x	x	x	x	x
<i>Psoyoil_{d,SP}</i>	x	x	x	x	x
<i>Pmeal_{d,SP}</i>	x	x	x	x	x
<i>Psoy_{x,PR}</i>	x				
<i>Psoy_{d,PR}</i>		x			
<i>Psoy_{d,SP}</i>			x		
<i>Psoy_{d,RS}</i>				x	
<i>Psoy_{d,MT}</i>					x
Deterministic regressor	Optimal lag order in the VAR(p)				
None	2	2	2	2	2
Constant	2	2	2	2	2
Trend	1	2	2	2	2
Cointegration rank (r)					
Trace test					
None	1	1	1	1	1
Constant	1	1	1	1	1
Trend	-	1	1	1	1
Maximal Eigenvalue test					
None	1	1	1	1	1
Constant	1	1	1	1	1
Trend	-	1	1	NC	NC

Source: prepared by the authors.

Note: x = inclusion of the variable in the model; NC = no cointegration.

Table 16 shows the results of VECMs regarding the soybean complex, evaluating all cases presented in Table 15. First, the cointegrating vectors ($\hat{\beta}$) are significant and present the same signal pattern across several specifications. The inclusion of constant does not affect the magnitude of the coefficients, but the coefficients extent in models with a trend is different,

mainly in SB2 and SB5¹⁶. We choose to analyze the effects of SB3 specification because it refers to the prices of soybean, soybean meal, and soybean oil from the same location (São Paulo State).

The $\hat{\beta}$ show that an increase of 1% in soybean price at Mogiana-SP ($Psoy_{d,SP}$) decreases the biodiesel price in 5.69% in SB3 models without deterministic term or constant, or reduces in 8.61% in SB3 model with a trend (Table 16). The reason for this effect is the choice mechanism by producers, if soybean price upsurges in the short-term, the soybean cultivation starts to expand, resulting in the excess of soybean supply in the future, decreasing the cost of raw material for crushers and, finally, dropping the biodiesel price.

Table 16. Cointegrating vector ($\hat{\beta}$) for models of soybean complex

Model	SB1	SB2	SB3	SB4	SB5
	$Psoy_{x,PR}$	$Psoy_{d,PR}$	$Psoy_{d,SP}$	$Psoy_{d,RS}$	$Psoy_{d,MT}$
Deterministic term in the cointegrating vector: none					
<i>Pbio</i>	1.000	1.000	1.000	1.000	1.000
<i>Psoyoil_{d,SP}</i>	-3.477 *** (-4.321)	-2.505 *** (-5.207)	-1.967 *** (-6.354)	-1.585 *** (-4.432)	-1.442 *** (-5.927)
<i>Pmeal_{d,SP}</i>	-6.945 *** (-5.303)	-5.133 *** (-5.694)	-3.403 *** (-5.896)	-2.715 *** (-4.547)	-1.543 *** (-4.182)
<i>Psoy_{i,j}</i>	12.572 *** (6.064)	7.776 *** (6.184)	5.693 *** (6.947)	4.480 *** (5.697)	2.516 *** (5.644)
Deterministic term in the cointegrating vector: constant					
<i>Pbio</i>	1.000	1.000	1.000	1.000	1.000
<i>Psoyoil_{d,SP}</i>	-3.481 *** (-4.320)	-2.503 *** (-5.208)	-1.967 *** (-6.354)	-1.586 *** (-4.431)	-1.441 *** (-5.927)
<i>Pmeal_{d,SP}</i>	-6.953 *** (-5.303)	-5.127 *** (-5.693)	-3.403 *** (-5.896)	-2.718 *** (-4.547)	-1.542 *** (-4.182)
<i>Psoy_{i,j}</i>	12.587 *** (6.064)	7.767 *** (6.183)	5.693 *** (6.947)	4.483 *** (5.697)	2.514 *** (5.642)
<i>Constant</i>	-4.171 (-1.189)	3.920 * (1.699)	0.336 (0.236)	0.180 (0.100)	0.586 (0.457)
Deterministic term in the cointegrating vector: trend					
<i>Pbio</i>		1.000	1.000	1.000	1.000
<i>Psoyoil_{d,SP}</i>		-8.436 *** (-4.537)	-3.026 *** (-5.172)	-1.504 *** (-3.236)	-8.165 *** (-5.010)
<i>Pmeal_{d,SP}</i>		-16.661 *** (-5.979)	-5.099 *** (-5.973)	-2.586 *** (-4.355)	-8.277 *** (-4.659)
<i>Psoy_{i,j}</i>		25.548 *** (6.070)	8.611 *** (6.405)	4.263 *** (4.748)	13.932 *** (5.184)
<i>Trend</i>		-0.011 * (-1.744)	-0.003 (-1.327)	0.000 (0.135)	-0.020 *** (-3.353)

Source: prepared by the authors with RStudio 1.2.1578.

Note: *t*-statistics in parentheses; the coefficients must be interpreted with inverted signals; *** significant at 1%; ** significant at 5%; * significant at 10%.

The mills decide to produce biodiesel or soybean oil based on the prices, generating soybean meal from the crushing process. If soybean oil price increases, the crushers allocate the

¹⁶ The models regarding the soybean complex do not present residual autocorrelation and existence of heteroscedasticity. There is no normality of residuals, but all models present structural stability. In Appendix D, Table D4 presents the diagnostic tests.

production in this segment, reducing the biodiesel supply and, consequently, expanding the price of biodiesel. According to Table 16, if the price of soybean oil rises 1%, biodiesel price increases by 1.96% in the SB3 model with constant, and 3.02% in the SB3 model with a trend. If the price of soybean meal decreases, there is more soybean oil or biodiesel production since they are co-products. As a consequence, biodiesel and soybean oil prices tend to reduce and vice-versa. These relationships are seen in Table 16, one growth (reduction) of 1% in soybean meal price increments (drops) biodiesel price between 3.40% and 5.17% in the SB3 models.

In Table 16, the prices of different products of soybean complex from several locations are important to determine the biodiesel price. However, it is crucial to include economic restrictions to evaluate specific effects, since unrestricted forms present some contemporaneous and/or long-run coefficients with no economic meaning. Assuming the restrictions suggested in equations (28), (29), and (30), we estimate a SVECM, compute impulse response functions, and forecast the error variance decomposition for the SB3 model with constant. We calculate bootstrap error bands of the impulse response coefficients with 1000 runs for 24 months ahead. Figure 8 presents the impulse response functions for SVECM(1)-SB3 model with a constant (in Appendix C, Figure C4 shows the results for the unrestricted version). The expected response of biodiesel price to a 1% increase in soybean price tends to be negative in the time horizon, steadying in -0.085% after 6 months. An increase of 1% in soybean meal price results in a positive effect on biodiesel price, stabilizing in 0.099% in 8 months. The soybean oil price presents a smaller effect, a shock of 1% outcomes in a steady coefficient of 0.015 in 8 months for biodiesel price. Regarding other goods of the soybean complex, a 1% growth in soybean price implies $+0.019\%$ in soybean oil price after 9 months and $+0.051\%$ in soybean meal price after 4 months.

Figure 8. Responses to economic shocks in Brazilian soybean complex, SVECM(1)-SB3 with constant in the cointegrating vector (95% bootstrap confidence intervals, 1000 runs)

Source: prepared by the authors with RStudio 1.2.1578.

Table 17 shows the forecast error variance decomposition for unrestricted VECM(1)-SB3 and SVECM(1)-SB3, both with constant in the cointegrating vector. In the unrestricted specification, the biodiesel price formation is significantly independent of other variables included because, after 24 months, 74.26% of the forecast error variance is explained by *Pbio*. After including restrictions, we observe that soybean meal and soybean prices became important factors to determine biodiesel price because, in the first month, their forecast error variance achieved 42.95% and 21.51%, respectively, expanding in the time horizon. Soybean oil price is not decisive for the biodiesel price in the short-run. Biodiesel price determines 7.88% of the forecast error variance of soybean oil price in VECM(1)-SB3 considering 24 months ahead, while in SVECM(1)-SB3, it explains 16.58% for the same period.

Table 17. Forecast error variance decomposition, models SB3

Period	Model							
	VECM(1)-SB3				SVECM(1)-SB3			
	<i>Pbio</i> (%)	<i>Psoy_{oil}_{d,SP}</i> (%)	<i>Pmeal_{d,SP}</i> (%)	<i>Psoy_{d,SP}</i> (%)	<i>Pbio</i> (%)	<i>Psoy_{oil}_{d,SP}</i> (%)	<i>Pmeal_{d,SP}</i> (%)	<i>Psoy_{d,SP}</i> (%)
Variable: <i>Pbio</i>								
1	100.00%	0.00%	0.00%	0.00%	35.54%	0.00%	42.95%	21.51%
2	98.93%	0.04%	0.25%	0.78%	33.88%	0.02%	42.95%	23.15%
3	96.14%	0.25%	0.79%	2.82%	31.67%	0.08%	43.33%	24.92%
4	92.91%	0.58%	1.39%	5.12%	29.95%	0.18%	43.61%	26.26%
5	89.91%	0.93%	1.94%	7.23%	28.60%	0.28%	43.84%	27.28%
6	87.35%	1.25%	2.41%	9.00%	27.54%	0.37%	44.03%	28.06%
12	79.08%	2.34%	3.94%	14.64%	24.30%	0.68%	44.62%	30.40%
24	74.26%	3.00%	4.84%	17.90%	22.43%	0.88%	44.97%	31.73%
Variable: <i>Psoy_{oil}_{d,SP}</i>								
1	0.25%	99.75%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
2	2.21%	97.09%	0.70%	0.00%	3.75%	91.33%	2.30%	2.62%
3	3.55%	95.00%	1.43%	0.03%	6.23%	88.11%	2.56%	3.10%
4	4.54%	93.40%	1.96%	0.09%	8.42%	85.51%	2.80%	3.28%
5	5.27%	92.22%	2.34%	0.17%	10.10%	83.67%	2.94%	3.29%
6	5.81%	91.35%	2.60%	0.24%	11.39%	82.30%	3.05%	3.27%
12	7.22%	89.04%	3.27%	0.47%	14.92%	78.64%	3.32%	3.12%
24	7.88%	87.96%	3.58%	0.58%	16.58%	76.94%	3.45%	3.02%
Variable: <i>Pmeal_{d,SP}</i>								
1	0.08%	4.21%	95.71%	0.00%	0.00%	0.00%	100.00%	0.00%
2	5.11%	5.25%	88.06%	1.58%	13.19%	0.00%	64.43%	22.38%
3	6.41%	5.49%	85.95%	2.14%	17.58%	0.00%	52.47%	29.95%
4	7.13%	5.61%	84.88%	2.38%	20.92%	0.00%	44.81%	34.27%
5	7.58%	5.69%	84.27%	2.46%	23.24%	0.01%	40.24%	36.51%
6	7.89%	5.76%	83.86%	2.49%	25.02%	0.02%	37.09%	37.87%
12	8.70%	5.94%	82.88%	2.49%	30.11%	0.08%	29.19%	40.62%
24	9.08%	6.03%	82.42%	2.47%	32.74%	0.11%	25.37%	41.77%
Variable: <i>Psoy_{d,SP}</i>								
1	1.30%	12.23%	36.44%	50.03%	0.00%	0.00%	0.00%	100.00%
2	3.18%	12.63%	48.71%	35.48%	2.59%	0.02%	1.08%	96.32%
3	5.95%	13.73%	54.53%	25.78%	9.19%	0.52%	1.01%	89.28%
4	8.38%	14.74%	57.24%	19.64%	16.03%	1.39%	0.81%	81.77%
5	10.26%	15.51%	58.52%	15.71%	21.70%	2.28%	0.63%	75.39%
6	11.65%	16.06%	59.18%	13.10%	26.03%	3.04%	0.50%	70.43%
12	15.18%	17.46%	60.20%	7.16%	37.37%	5.23%	0.21%	57.19%
24	16.72%	18.06%	60.53%	4.69%	42.26%	6.22%	0.09%	51.42%

Source: prepared by the authors with RStudio 1.2.1578.

The forecast error variance of the soybean meal price is mainly explained by the own price in the unrestricted form, but when accounting for the economic structure, soybean price defines 41.77%, and biodiesel price 32.74% two years later. For soybean price, VECM(1)-SB3 sets soybean meal price as the main source of explanation, being 60.53% after 24 months, changing to its price (51.42%) and biodiesel price (42.26%) in the restricted form.

3.4.3. Results for blended diesel price

We define the optimal unrestricted VAR models for blended diesel price using 6 lags as the maximum length, AIC as information criterion, and including monthly seasonal dummies. The lag order is 2 or 3, depending on the deterministic regressors in the model. Table 18 shows the number of lags in the VAR(p) and the cointegration rank.

Table 18. Lag-order selection in VAR(p) and cointegration rank (r) for models of blended diesel

Variables	Model				
	DC1	DC2	DC3	DC4	DC5
<i>Pdc</i>	x	x	x	x	x
<i>Qdc</i>	x	x	x	x	x
<i>Pda</i>	x	x	x	x	x
<i>Pbio</i>	x	x	x	x	x
<i>Psoy_{x,PR}</i>	x				
<i>Psoy_{d,PR}</i>		x			
<i>Psoy_{d,SP}</i>			x		
<i>Psoy_{d,RS}</i>				x	
<i>Psoy_{d,MT}</i>					x
Deterministic regressor	Optimal lag order in the VAR(p)				
None	3	2	2	2	2
Constant	3	2	2	2	2
Trend	3	2	3	3	2
Cointegration rank (r)					
Trace test					
None	1	1	1	1	1
Constant	NC	1	1	1	1
Trend	1	1	1	1	1
Maximum Eigenvalue test					
None	1	1	1	1	1
Constant	1	1	1	1	1
Trend	NC	1	1	1	NC

Note: x = inclusion of the variable in the model; NC = no cointegration.

According to Table 18, most models presented at least one cointegrating vector in Trace and Maximum Eigenvalue tests. For the Trace test in the DC1 model with constant, there is no cointegration, as well as for DC1 and DC5 models with a trend in the Maximum Eigenvalue test.

The additional information on these tests can be found in Table D8 (Appendix D)¹⁷. Table 19 shows the results for the blended diesel price, including soybean prices from several locations and using different specifications. The inclusion of constant in the cointegrating vector seems to be a good approximation since this term was significant. Models with a trend presented coefficients slightly different from other versions, but the signals were the same for all cases.

Table 19. Cointegrating vector ($\hat{\beta}$) for models of blended diesel price

Model	DC1	DC2	DC3	DC4	DC5
	$Psoy_{x,PR}$	$Psoy_{d,PR}$	$Psoy_{d,SP}$	$Psoy_{d,RS}$	$Psoy_{d,MT}$
Deterministic term in the cointegrating vector: none					
<i>Pdc</i>	1.000	1.000	1.000	1.000	1.000
<i>Qdc</i>	0.849 *** (5.936)	1.080 *** (6.187)	1.300 *** (6.366)	1.166 *** (6.355)	1.356 *** (6.085)
<i>Pda</i>	-0.311 *** (-2.579)	-0.181 (-1.164)	-0.109 (-0.604)	-0.209 (-1.281)	-0.100 (-0.503)
<i>Pbio</i>	0.376 *** (4.877)	0.465 *** (4.757)	0.549 *** (4.821)	0.491 *** (4.838)	0.574 *** (4.639)
<i>Psoy_{i,j}</i>	-0.214 *** (-2.838)	-0.188 ** (-2.162)	-0.303 *** (-2.929)	-0.256 *** (-2.845)	-0.240 ** (-2.293)
Deterministic term in the cointegrating vector: constant					
<i>Pdc</i>	1.000	1.000	1.000	1.000	1.000
<i>Qdc</i>	0.839 *** (5.944)	1.070 *** (6.191)	1.292 *** (6.369)	1.154 *** (6.359)	1.350 *** (6.087)
<i>Pda</i>	-0.315 *** (-2.656)	-0.186 (-1.206)	-0.112 (-0.625)	-0.214 (-1.327)	-0.103 (-0.518)
<i>Pbio</i>	0.370 *** (4.875)	0.460 *** (4.753)	0.545 *** (4.819)	0.485 *** (4.834)	0.571 *** (4.637)
<i>Psoy_{i,j}</i>	-0.209 *** (-2.813)	-0.185 ** (-2.149)	-0.300 *** (-2.920)	-0.252 *** (-2.830)	-0.238 ** (-2.286)
<i>Constant</i>	-19.088 *** (-6.007)	-24.565 *** (-6.266)	-29.166 *** (-6.351)	-26.133 *** (-6.383)	-30.757 *** (-6.135)
Deterministic term in the cointegrating vector: trend					
<i>Pdc</i>	1.000	1.000	1.000	1.000	1.000
<i>Qdc</i>	0.817 *** (5.861)	0.443 *** (6.917)	0.577 *** (6.500)	0.697 *** (6.404)	0.506 *** (6.717)
<i>Pda</i>	-0.328 *** (-2.833)	-0.529 *** (-9.430)	-0.438 *** (-5.991)	-0.399 *** (-4.451)	-0.498 *** (-7.536)
<i>Pbio</i>	0.354 *** (3.727)	0.086 * (1.893)	0.220 *** (3.686)	0.292 *** (3.998)	0.108 ** (2.060)
<i>Psoy_{i,j}</i>	-0.201 *** (-2.746)	-0.018 (-0.566)	-0.077 * (-1.802)	-0.126 ** (-2.478)	-0.024 (-0.670)
<i>Trend</i>	0.000 (-0.094)	-0.001 *** (-2.921)	0.000 (-0.692)	0.000 (-0.141)	-0.001 ** (-2.543)

Source: prepared by the authors with RStudio 1.2.1578.

Note: *t*-statistics in parentheses; coefficients must be interpreted with inverted signals; *** significant at 1%; ** significant at 5%; * significant at 10%.

The outcomes regarding $\hat{\beta}$ present important findings. First, the price of petroleum diesel (*Pda*) positively affects the price of blended diesel, an increase of 1% in *Pda* at refineries rises *Pdc* for consumers between 0.31% and 0.33% in DC1 models. Second, coefficients concerning

¹⁷ In Appendix D, Table D5 presents the diagnostic tests. The models regarding the blended diesel price do not present residual autocorrelation and heteroscedasticity. There is no normality of residuals, but all models present structural stability.

biodiesel price present opposite effect, an increase in biodiesel price reduces the price of blended diesel by 0.22-0.54% in DC3 models (Table 19). The rationale behind the last result is given by the following argument: if crushers observe an increase in biodiesel price in the short-run, they tend to produce more biodiesel creating an excess of supply in the future (in the next auctions), reducing biodiesel price and, consequently, the blended diesel price in the long term due to blend mandate. Third, soybean price is a crucial component for biodiesel price formation and, subsequently, for blended diesel price. The models suggest that soybean prices at Paranaguá Port ($Psoy_{x,PR}$), Maringá-PR ($Psoy_{d,PR}$), Mogiana-SP ($Psoy_{d,SP}$), Passo Fundo-RS ($Psoy_{d,RS}$), and Rondonópolis-MT ($Psoy_{d,MT}$) are important to determine the price of diesel C in Brazil. The complementarity between fossil fuels and biofuels in Brazil creates the following structure: an expansion in soybean price rises the prices of derivatives as soybean meal, soybean oil, and biodiesel, as a consequence, the diesel C price tends to increase since there is an obligatory blend. It is important to highlight that the magnitude of effects depends on location, an increase of 1% in $Psoy_{d,PR}$ augments diesel C price in 0.18%, but for $Psoy_{d,SP}$ the effect is +0.30%, both in models with constant. Fourth, a growth in quantity drops the blended diesel price. For example, in the DC5 model with constant considering soybean price at Rondonópolis (MT), this effect reaches -1.35%.

We run the DC3 model with constant in the cointegrating vector including economic restrictions proposed by equations (32), (33), and (34), resulting in the SVECM(1)-DC3 model. From this specification, we calculate impulse response functions and forecast error variance decomposition using bootstrap error bands with 1000 runs for 24 months forward. Figure 9 presents impulse response functions (in Appendix C, Figure C5 shows the results for the unrestricted version). The response of diesel C price for a 1% growth in the quantity of diesel C is positive in the first month (+0.002%), steady in a negative value in the third period, -0.001%. An expansion of 1% in petroleum diesel price causes a positive effect on blended diesel price, stabilizing in 0.024% after 3 months. A biodiesel price rise of 1% causes a short-run coefficient of 0.003 in the fourth month for diesel C price. If there is an expansion of 1% in soybean price, the blended diesel price tends to -0.001%. It is important to highlight that an expansion of 1% in the blended diesel price tends to reduce the quantity permanently by 0.011%. Another key relationship is the response of biodiesel price when there is a shock of 1% in soybean price, the effect is +0.010% in two years.

Figure 9. Responses to economic shocks in the model of blended diesel price, SVECM(1)-DC3 with constant in the cointegrating vector (95% bootstrap confidence interval, 1000 runs)

Source: prepared by the authors with RStudio 1.2.1578.

Table 20 displays the forecast error variance decomposition for VECM(1)-DC3 and SVECM(1)-DC3. In VECM(1)-DC3, the price of diesel C is expressively independent of other variables because 24 months ahead its share is 83.95%, and the share of petroleum diesel price is 10.56%.

Table 20. Forecast error variance decomposition, models DC3

Period	Model									
	VECM(1)–DC3					SVECM(1)–DC3				
	<i>Pdc</i> (%)	<i>Qdc</i> (%)	<i>Pda</i> (%)	<i>Pbio</i> (%)	<i>Psoy_{d,SP}</i> (%)	<i>Pdc</i> (%)	<i>Qdc</i> (%)	<i>Pda</i> (%)	<i>Pbio</i> (%)	<i>Psoy_{d,SP}</i> (%)
Variable: <i>Pbio</i>										
1	100.00%	0.00%	0.00%	0.00%	0.00%	32.44%	0.43%	65.56%	1.46%	0.11%
2	92.14%	0.67%	6.11%	0.80%	0.27%	26.79%	0.26%	71.17%	1.63%	0.15%
3	88.76%	1.41%	8.33%	1.14%	0.37%	24.15%	0.22%	73.75%	1.70%	0.17%
4	87.56%	2.00%	8.94%	1.15%	0.35%	22.80%	0.21%	75.12%	1.70%	0.17%
5	86.85%	2.47%	9.26%	1.11%	0.31%	21.95%	0.20%	76.01%	1.68%	0.16%
6	86.29%	2.84%	9.51%	1.07%	0.28%	21.33%	0.20%	76.66%	1.66%	0.15%
12	84.75%	3.93%	10.20%	0.95%	0.18%	19.59%	0.20%	78.50%	1.59%	0.12%
24	83.95%	4.49%	10.56%	0.88%	0.13%	18.60%	0.20%	79.56%	1.55%	0.10%
Variable: <i>Qdc</i>										
1	0.94%	99.06%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
2	0.88%	97.58%	0.47%	1.04%	0.03%	0.06%	98.53%	1.14%	0.03%	0.23%
3	1.10%	95.36%	0.95%	2.10%	0.50%	2.51%	93.06%	2.44%	1.64%	0.35%
4	1.40%	91.94%	1.24%	3.95%	1.47%	3.75%	88.37%	3.41%	3.64%	0.83%
5	1.80%	88.21%	1.48%	5.77%	2.73%	4.93%	82.39%	4.94%	6.00%	1.74%
6	2.18%	84.56%	1.68%	7.53%	4.05%	5.79%	77.13%	6.18%	8.15%	2.74%
12	3.76%	69.70%	2.45%	14.36%	9.72%	8.76%	57.02%	11.04%	16.09%	7.08%
24	5.02%	57.80%	3.06%	19.79%	14.32%	10.85%	42.55%	14.51%	21.80%	10.30%
Variable: <i>Pda</i>										
1	55.39%	0.04%	44.57%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
2	42.46%	0.40%	56.19%	0.82%	0.14%	23.43%	1.76%	74.80%	0.00%	0.00%
3	38.00%	0.50%	60.28%	1.06%	0.16%	37.19%	2.24%	60.56%	0.01%	0.01%
4	36.27%	0.58%	61.92%	1.08%	0.15%	42.91%	2.44%	54.64%	0.01%	0.01%
5	35.28%	0.63%	62.87%	1.08%	0.14%	46.28%	2.51%	51.20%	0.00%	0.00%
6	34.59%	0.66%	63.53%	1.08%	0.13%	48.70%	2.56%	48.73%	0.00%	0.00%
12	32.78%	0.76%	65.26%	1.09%	0.11%	55.33%	2.67%	42.00%	0.00%	0.00%
24	31.86%	0.81%	66.14%	1.10%	0.10%	58.92%	2.72%	38.35%	0.00%	0.00%
Variable: <i>Pbio</i>										
1	0.12%	3.80%	5.65%	90.43%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
2	0.35%	6.99%	8.64%	83.81%	0.21%	0.12%	1.86%	0.28%	97.71%	0.03%
3	0.47%	9.22%	10.40%	79.30%	0.62%	0.17%	5.04%	0.75%	93.96%	0.08%
4	0.53%	11.06%	11.12%	76.29%	1.00%	0.15%	8.45%	1.49%	89.54%	0.37%
5	0.60%	12.42%	11.48%	74.18%	1.33%	0.13%	11.36%	2.27%	85.44%	0.79%
6	0.65%	13.43%	11.72%	72.61%	1.59%	0.12%	13.67%	2.94%	82.04%	1.24%
12	0.82%	16.14%	12.31%	68.38%	2.35%	0.08%	20.22%	4.91%	71.98%	2.81%
24	0.90%	17.52%	12.61%	66.22%	2.75%	0.06%	23.69%	5.96%	66.59%	3.69%
Variable: <i>Psoy_{d,SP}</i>										
1	1.73%	0.15%	4.10%	0.29%	93.73%	0.00%	0.00%	0.00%	0.00%	100.00%
2	2.68%	0.11%	4.67%	0.30%	92.24%	0.45%	0.00%	0.77%	0.05%	98.73%
3	3.00%	1.12%	4.58%	0.51%	90.79%	0.40%	0.39%	0.85%	0.03%	98.33%
4	2.94%	2.51%	4.53%	0.82%	89.19%	0.31%	0.95%	0.68%	0.07%	97.99%
5	2.81%	3.96%	4.55%	1.17%	87.51%	0.25%	1.57%	0.55%	0.15%	97.48%
6	2.68%	5.23%	4.57%	1.50%	86.01%	0.21%	2.10%	0.46%	0.25%	96.98%
12	2.27%	9.24%	4.66%	2.58%	81.24%	0.12%	3.76%	0.23%	0.61%	95.28%
24	2.05%	11.36%	4.71%	3.16%	78.72%	0.08%	4.63%	0.11%	0.80%	94.38%

Source: prepared by the authors with RStudio 1.2.1578.

The quantity of blended diesel is important to determine its forecast error variance. The price of diesel A depends, mainly, on the forecast error variance of blended diesel at the pump

(55.39%), and pure petroleum diesel (44.57%) in the first month, but in the future, *Pda*'s share tends to increase achieving 66.14% after two years. The soybean price represents a small share in biodiesel price forecast error variance in VECM(1)-DC3, being determined by itself (68.38%), the quantity (16.14%), and price of diesel A (12.31%) when observing 12 periods ahead. The quantity of diesel C explains 11.36% of the forecast error variance of soybean price at Mogiana-SP 24 months forward.

The SVECM-DC3 version shows expressive changes. *Pda* presents a significant share in the forecast error variance of *Pdc*, representing 65.56% in the first month. *Qdc* is mainly explained by itself in the first period, dropping to 42.55% in two years. The price of pure petroleum diesel (*Pda*) is expressively self-determining in the initial periods, but it tends to be determined by the blended fuel price in the future since its share achieves 55.33% in 12 months. The price of biodiesel is dependent on blended diesel quantity, confirming the importance of the blend mandate for this price. Finally, *Psoy_{d,SP}* is considered autonomous in this model.

3.4.4. Results for blended diesel demand

We evaluate the demand for blended diesel in Brazil following the steps described before. First, for unrestricted VAR models, we choose a maximum of 6 lags considering AIC as the criterion and adjusting for monthly seasonal dummies. The model with no deterministic term indicates 2 lags, while models with constant or trend suggest 4 lags as optimal in the VAR. Second, we checked the cointegration, where Trace and Maximum Eigenvalue tests indicate $r = 1$ for all cases at 1% of significance¹⁸.

The unrestricted VECMs are presented in Table 21¹⁹. All models revealed signals according to economic literature. The version with constant in the cointegrating vector is more suitable, since the term was significant in this specification, being the long-run elasticities given by the $\hat{\beta}$. As the GDP is a proxy of income, the long-run income elasticity of blended diesel demand is 0.825, meaning that a growth of 1% in the income upsurges the demand of blended diesel in 0.825%. The coefficient concerning the long-run price elasticity of blended diesel demand is -0.184, although it is not significant. Our results on elasticities are in accordance with the

¹⁸ Some cases pointed $r = 2$, such as the Trace test with no deterministic term at 10%, with constant at 5%, and with trend at 10%; and the Maximum Eigenvalue test with constant at 5%, and trend at 10%. The test statistics are presented in Table D9, Appendix D.

¹⁹ The results of the alternative models are shown in Table D10 (Appendix D). Table D6 displays the diagnostic tests. The models regarding blended diesel demand do not present residual autocorrelation, the versions with constant or trend in the cointegrating vector do not present heteroscedasticity. We reject the normality of residuals, but models with constant or trend have structural stability.

empirical literature. Dahl (2012) evaluated the price elasticity and income elasticity of diesel demand for 124 countries. The author found an average diesel price elasticity of -0.16 . For countries with per capita income smaller than US\$ 15 thousand per year (in US\$ of 2006) and diesel price higher than US\$ 2.50 per gallon, the price elasticity was -0.38 , while in countries where the price was smaller than US\$ 2.50 per gallon and per capita income higher than US\$ 15 thousand per year, the price elasticity was -0.13 . For Brazil, the author observed a diesel price elasticity of -0.25 and income elasticity of 0.90 , while for the United States these estimates were -0.07 and 1.00 , respectively. Cardoso and Jesus (2018), using data between January 2003 and March 2018 and Autoregressive Distributed Lag models, observed a long-run price elasticity for diesel demand in Brazil ranging from -0.72 to -0.85 , and a long-run income elasticity between 0.99 and 1.04 . Rodrigues and Losekann (2015), considering annual data regarding all Brazilian states, applied dynamic panel analysis to specify the diesel demand. Their results pointed a price elasticity of diesel demand of -0.197 and income elasticity equals to 0.099 . Huntington et al. (2019) analyzed a set of elasticities between developing economies such as Brazil, China, India, Mexico, Russia, Chile, South Korea, and South Africa and higher-income countries of the Organization for Economic Co-operation and Development (OECD) considering Dahl's (2004) study. For diesel demand in developing economies, the authors found an average diesel price elasticity of -0.50 in the long term and -0.41 in the short term, while in OECD countries the long and short-run diesel price elasticities were -0.67 and -0.13 , respectively. For income, Huntington et al. (2019) reported a long-run elasticity of 1.13 for OECD members, being the short-run income elasticity equals to 0.55 .

Table 21. Cointegrating vector ($\hat{\beta}$) for blended diesel demand

Vector	None	Constant	Trend
<i>Qdc</i>	1.000	1.000	1.000
<i>Pdc</i>	0.002 (0.017)	0.184 (1.550)	0.024 (0.178)
<i>Gdp</i>	-1.015 *** (-12.643)	-0.825 *** (-10.843)	-1.048 *** (-7.486)
<i>Constant</i>		-11.565 *** (-10.323)	
<i>Trend</i>			4.25E-04 (1.448)

Source: prepared by the authors with RStudio 1.2.1578.

Note: *t*-statistics in parentheses; the coefficients must be interpreted with inverted signals; *** significant at 1%; ** significant at 5%; * significant at 10%.

Choosing the model with constant in the cointegrating vector, we constructed a structural model. We restricted the contemporaneous relationships given by matrix *A* of coefficients as described in equations (36), (37), and (38), resulting in the model SVECM(3)-D1 for blended

diesel demand. The impulse response functions using bootstrap error bands with 1000 runs for 24 months ahead are presented in Figure 10. The response of blended diesel consumption regarding an increase of 1% in diesel C price reveals a positive impact in the first month followed by a cyclical movement up to 11th month when the effects steady in -0.002% . One shock of 1% in GDP expands the level of blended diesel consumption, occurring a cyclical movement until the 10th month. After this period, there is a small growth achieving equilibrium in $+0.015\%$. The price of blended diesel presents a temporary effect on GDP, there is a growth until the third month ($+0.003\%$), declining and tending to zero after one year.

Figure 10. Responses to economic shocks in Brazilian blended diesel demand, SVECM(3)-D1 with constant in the cointegrating vector (95% bootstrap confidence interval, 1000 runs)

Source: prepared by the authors with RStudio 1.2.1578.

The forecast error variance of blended diesel demand presents important findings (Table 22). In the first month, the quantity (Qdc) is mainly explained by itself, but the price of diesel C shows an increasing share until the fourth month, 2.36% for VECM(3)-D1, and 10.21% for SVECM(3)-D1. However, these shares drop months ahead. The portion of GDP rise to 46.43% and 48.08% in two years, for both specifications. The price of blended diesel is meaningfully independent since the forecast error variance of Pdc achieves 96.23% and 94.20% after 24 months, considering both models. Finally, GDP forecast error variance is driven by itself in VECM(3)-D1, although there is a reduction of the share until the fourth month, its percentage tends to expand. After we restricted the model, the results are more realistic because GDP is self-

determining, that is, it is explained by itself or other factors that are not included in the model, which impact the Brazilian economy.

Table 22. Forecast error variance decomposition, models D1

Period	Model					
	VECM(3)-D1			SVECM(3)-D1		
	<i>Qdc</i> (%)	<i>Pdc</i> (%)	<i>Gdp</i> (%)	<i>Qdc</i> (%)	<i>Pdc</i> (%)	<i>Gdp</i> (%)
Variable: <i>Qdc</i>						
1	100.00%	0.00%	0.00%	97.30%	0.52%	2.18%
2	93.61%	1.00%	5.39%	91.06%	5.24%	3.70%
3	94.00%	0.94%	5.05%	90.55%	5.75%	3.70%
4	90.28%	2.36%	7.36%	84.97%	10.21%	4.82%
5	86.17%	2.28%	11.55%	81.37%	9.78%	8.84%
6	81.97%	2.16%	15.87%	79.94%	9.62%	10.43%
12	67.96%	1.95%	30.10%	64.89%	7.88%	27.23%
24	51.93%	1.64%	46.43%	45.92%	6.00%	48.08%
Variable: <i>Pdc</i>						
1	0.01%	99.99%	0.00%	0.00%	100.00%	0.00%
2	0.79%	99.14%	0.07%	0.16%	99.06%	0.78%
3	0.88%	99.04%	0.08%	0.11%	99.18%	0.71%
4	0.69%	98.33%	0.97%	1.29%	98.01%	0.70%
5	0.64%	97.95%	1.41%	2.35%	97.00%	0.65%
6	0.67%	97.54%	1.79%	3.08%	96.37%	0.55%
12	0.65%	96.69%	2.66%	4.47%	95.26%	0.27%
24	0.62%	96.23%	3.15%	5.66%	94.20%	0.14%
Variable: <i>Gdp</i>						
1	15.34%	2.14%	82.52%	0.00%	0.00%	100.00%
2	20.23%	1.64%	78.13%	0.21%	2.13%	97.67%
3	26.90%	1.35%	71.74%	0.17%	3.72%	96.11%
4	27.45%	1.20%	71.36%	0.33%	3.22%	96.45%
5	24.90%	1.07%	74.03%	1.09%	2.85%	96.05%
6	23.35%	0.97%	75.68%	1.29%	2.50%	96.21%
12	20.21%	0.85%	78.94%	3.82%	1.18%	94.99%
24	18.11%	0.76%	81.13%	5.78%	0.54%	93.68%

Source: prepared by the authors with RStudio 1.2.1578.

3.5. Conclusion

The Brazilian concerns regarding the environmental agenda led the government to create the National Biodiesel Production and Use Program (PNPB) in 2004. This policy established the obligatory blend of biodiesel in petroleum diesel nationwide, boosting different sectors of family farming and agribusiness. This paper focused on understanding the use of soybean in the biodiesel production and the relationships between prices of products of the soybean complex and blended diesel. We employ unrestricted and structural versions of Vector Error Correction Models (VECMs) using monthly data from January 2006 to December 2018.

First, we stressed the linkages between prices of soybean grains, soybean meal, soybean oil, and biodiesel. We observe that soybean prices from different locations in Brazil are important to determine the biodiesel price. An unexpected shock in soybean prices tends to reduce the biodiesel price in the long-run because soybean producers start to cultivate more in the short-run,

creating excesses of soybean supply in the future and reducing biodiesel price. Soybean meal is a co-product of soybean oil and biodiesel production. Thus, an increase in the soybean meal price tends to be positively related to the biodiesel price. The crushing plants decide to produce biodiesel or soybean oil based on prices. Consequently, an expansion of soybean oil price upsurges the biodiesel price.

Second, we observed the relationships between soybean prices, biodiesel, petroleum diesel, blended diesel, and the quantity of blended diesel. Our estimates indicate that in the long-run, an increase in petroleum diesel price at refineries positively impacts the blended diesel price. But a biodiesel price rise negatively affects the blended diesel price. As a consequence, soybean prices are relevant to determine the price of blended diesel in Brazil. Third, we evaluated the demand for blended diesel. Our results are close to those found in the economic literature. The long-run income elasticity of demand for blended diesel is 0.825, indicating that the Brazilian demand is slightly elastic, and blended diesel is a normal good. Thus, from these long and short-run relationships, this paper fills a gap in the recent literature concerning the PNPB policy in Brazil, showing new insights regarding the production choice of soybean producers and crushing plants.

The biodiesel from soybeans presents a mitigation effect of pollution if compared to petroleum diesel. The expansion of the blend rate of biodiesel in petroleum diesel can result in less pollution. Thus, the blend mandate policy is great for the environment, promotes different sectors of agribusiness and family farming, creates improvements in the mills due to the necessity for new installations and machinery for the soybean crushing and biodiesel processing. However, the government needs to be careful when considering the rise of the biodiesel blend rate, because the markets of products of the soybeans complex and fuels present new connections. An expansion of the blend rate can lead mills to produce more biodiesel, affecting food prices in the long-run, that is, reducing the soybean meal price and increasing the soybean oil price. Furthermore, the blended diesel price tends to reduce with the expansion of the blend rate, since mills will choose to produce more biodiesel. Given the technical and economic viability, the blend mandate policy of biodiesel and petroleum diesel in Brazil can be taken as an example by other countries that have abundance in crops used for biodiesel production. This type of policy is adequate because it promotes the substitution of fossil fuels, contributing to the development of other segments.

Therefore, this paper added new insights regarding the relationships between fuel and food in Brazil, particularly, products of the soybean complex, diesel, and blended diesel. The obligatory blend of biodiesel and petroleum diesel was a milestone in the Brazilian fuel sector, presenting

new perspectives for crushing mills in the decision-making of production and regarding the level of greenhouse gas emissions since biodiesel tends to pollute less the environment.

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3.7. Appendix C: figures of chapter 3

Figure C1. Selected variables in level (Jan. 2006 - Dec. 2018)

Source: prepared by the authors with RStudio 1.2.1578.

Figure C2. Selected variables in the first difference (Jan. 2006 - Dec. 2018)
 Source: prepared by the authors with RStudio 1.2.1578.

Figure C3. Selected soybean prices in level and first difference (Jan. 2006 - Dec. 2018)
Source: prepared by the authors with RStudio 1.2.1578.

Figure C4. Responses to economic shocks in Brazilian soybean complex, VECM(1)-SB3 with constant in the cointegrating vector (95% bootstrap confidence interval, 1000 runs)

Source: prepared by the authors with RStudio 1.2.1578.

Figure C5. Responses to economic shocks in Brazilian model of price of diesel C, VECM(1)-DC3 with constant in the cointegrating vector (95% bootstrap confidence interval, 1000 runs)

Source: prepared by the authors with RStudio 1.2.1578.

Figure C6. Responses to economic shocks in Brazilian blended diesel demand, VECM(3)-D1 with constant in the cointegrating vector (95% bootstrap confidence interval, 1000 runs)
Source: prepared by the authors with RStudio 1.2.1578.

3.8. Appendix D: tables of chapter 3

Table D1. Biodiesel production in Brazilian states

State	Year					
	2008		2013		2018	
	(1000 m ³)	Share (%)	(1000 m ³)	Share (%)	(1000 m ³)	Share (%)
Acre (AC)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Alagoas (AL)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Amapá (AP)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Amazonas (AM)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Bahia (BA)	0.07	0.01%	0.19	0.01%	0.38	0.01%
Ceará (CE)	19.21	1.74%	84.19	3.09%	0.00	0.00%
Distrito Federal (DF)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Espírito Santo (ES)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Goiás (GO)	241.36	21.92%	575.71	21.14%	757.67	15.23%
Maranhão (MA)	36.17	3.28%	0.00	0.00%	0.00	0.00%
Mato Grosso (MT)	284.92	25.87%	418.48	15.37%	1,133.56	22.79%
Mato Grosso do Sul (MS)	0.00	0.00%	188.90	6.94%	324.48	6.52%
Minas Gerais (MG)	0.00	0.00%	88.02	3.23%	127.95	2.57%
Pará (PA)	2.63	0.24%	0.00	0.00%	0.00	0.00%
Paraíba (PB)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Paraná (PR)	7.29	0.66%	210.72	7.74%	597.35	12.01%
Pernambuco (PE)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Piauí (PI)	4.55	0.41%	0.00	0.00%	0.00	0.00%
Rio de Janeiro (RJ)	0.00	0.00%	8.89	0.33%	96.10	1.93%
Rio Grande do Norte (RN)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Rio Grande do Sul (RS)	306.06	27.79%	883.33	32.43%	1,479.47	29.74%
Rondônia (RO)	0.23	0.02%	13.55	0.50%	16.23	0.33%
Roraima (RR)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Santa Catarina (SC)	0.00	0.00%	38.36	1.41%	122.13	2.46%
São Paulo (SP)	185.59	16.85%	164.46	6.04%	233.65	4.70%
Sergipe (SE)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Tocantins (TO)	13.13	1.19%	48.69	1.79%	85.11	1.71%
Brazil	1101.21	100.00%	2723.49	100.00%	4974.08	100.00%

Source: prepared by the authors with data from ANP (2019).

Table D2. Soybean planted area, production, and productivity in Brazilian states

State	Harvest														
	2007/2008					2012/2013					2017/2018				
	Planted area (M ha)	Share (%)	Production (M tons)	Share (%)	Productivity (ton/ha)	Planted area (M ha)	Share (%)	Production (M tons)	Share (%)	Productivity (ton/ha)	Planted area (M ha)	Share (%)	Production (M tons)	Share (%)	Productivity (ton/ha)
Acre (AC)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	1.00
Alagoas (AL)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.01%	0.01	0.01%	3.00
Amapá (AP)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.02	0.06%	0.06	0.05%	2.90
Amazonas (AM)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.01%	0.00	0.00%	1.50
Bahia (BA)	0.91	4.25%	2.75	4.58%	3.04	1.28	4.62%	2.69	3.30%	2.10	1.60	4.55%	6.33	5.31%	3.96
Ceará (CE)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00
Distrito Federal (DF)	0.05	0.23%	0.15	0.25%	3.12	0.06	0.20%	0.19	0.23%	3.40	0.07	0.20%	0.25	0.21%	3.51
Espírito Santo (ES)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00
Goiás (GO)	2.18	10.23%	6.54	10.90%	3.00	2.89	10.41%	8.56	10.51%	2.97	3.39	9.64%	11.79	9.88%	3.48
Maranhão (MA)	0.42	1.98%	1.26	2.10%	2.99	0.59	2.11%	1.69	2.07%	2.88	0.95	2.71%	2.97	2.49%	3.12
Mato Grosso (MT)	5.68	26.63%	17.85	29.74%	3.15	7.82	28.19%	23.53	28.88%	3.01	9.52	27.08%	32.31	27.08%	3.39
Mato Grosso do Sul (MS)	1.73	8.12%	4.57	7.61%	2.64	2.02	7.27%	5.81	7.13%	2.88	2.67	7.60%	9.60	8.05%	3.59
Minas Gerais (MG)	0.87	4.08%	2.54	4.23%	2.92	1.12	4.04%	3.38	4.14%	3.01	1.51	4.29%	5.55	4.65%	3.68
Pará (PA)	0.07	0.33%	0.20	0.33%	2.83	0.17	0.62%	0.55	0.68%	3.21	0.55	1.56%	1.53	1.28%	2.78
Paraíba (PB)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00
Paraná (PR)	3.98	18.66%	11.90	19.82%	2.99	4.75	17.14%	15.91	19.52%	3.35	5.47	15.55%	19.17	16.07%	3.51
Pernambuco (PE)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00
Piauí (PI)	0.25	1.19%	0.82	1.36%	3.22	0.55	1.97%	0.92	1.13%	1.68	0.71	2.02%	2.54	2.13%	3.58
Rio de Janeiro (RJ)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00
Rio Grande do Norte (RN)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00
Rio Grande do Sul (RS)	3.83	17.99%	7.78	12.95%	2.03	4.62	16.65%	12.54	15.38%	2.71	5.69	16.19%	17.15	14.38%	3.01
Rondônia (RO)	0.10	0.47%	0.31	0.52%	3.12	0.17	0.61%	0.54	0.66%	3.21	0.33	0.95%	1.10	0.92%	3.28
Roraima (RR)	0.02	0.07%	0.05	0.08%	3.27	0.01	0.04%	0.03	0.04%	2.83	0.04	0.11%	0.12	0.10%	3.11
Santa Catarina (SC)	0.37	1.75%	0.95	1.58%	2.54	0.51	1.85%	1.58	1.94%	3.08	0.68	1.93%	2.31	1.93%	3.40
São Paulo (SP)	0.53	2.47%	1.45	2.41%	2.75	0.64	2.30%	2.05	2.52%	3.22	0.96	2.74%	3.41	2.86%	3.54
Sergipe (SE)	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00	0.00	0.00%	0.00	0.00%	0.00
Tocantins (TO)	0.33	1.56%	0.91	1.52%	2.74	0.55	1.98%	1.54	1.88%	2.79	0.99	2.81%	3.10	2.60%	3.14
Brazil	21.31	100.00%	60.02	100.00%	2.82	27.74	100.00%	81.50	100.00%	2.94	35.15	100.00%	119.28	100.00%	3.39

Source: prepared by the authors with data from CONAB (2019).

Table D3. Granger-causality test, F-statistics, and P-values

Variable	Statistic/ P-value	ΔPda	$\Delta Pbio$	ΔPdc	ΔQda	$\Delta Qbio$	ΔQdc	ΔGdp	$\Delta Psoy_{x,PR}$	$\Delta Psoy_{d,PR}$	$\Delta Psoy_{d,SP}$	$\Delta Psoy_{d,RS}$	$\Delta Psoy_{d,MT}$	$\Delta Pmeal_{d,SP}$	$\Delta Psoy_{oil}_{d,SP}$
ΔPda	F		0.482	1.811	0.411	0.775	0.402	1.604	1.028	0.780	1.405	0.697	0.988	0.940	0.806
	P-value		0.931	0.049	0.963	0.685	0.967	0.094	0.430	0.679	0.168	0.763	0.468	0.514	0.653
$\Delta Pbio$	F	0.969		1.586	0.942	0.346	0.910	1.449	1.508	2.138	1.284	1.659	1.405	1.358	0.777
	P-value	0.486		0.099	0.513	0.983	0.545	0.148	0.125	0.017	0.233	0.079	0.167	0.191	0.683
ΔPdc	F	3.407	0.529		0.536	0.797	0.511	1.786	1.268	1.136	1.611	1.115	1.362	1.445	1.265
	P-value	0.000	0.903		0.898	0.663	0.914	0.053	0.242	0.337	0.092	0.354	0.189	0.150	0.244
ΔQda	F	0.924	0.742	1.321		2.016	1.598	3.178	1.491	0.914	1.299	0.894	1.307	1.213	1.111
	P-value	0.531	0.718	0.211		0.025	0.095	0.000	0.131	0.541	0.224	0.561	0.219	0.279	0.357
$\Delta Qbio$	F	0.714	1.264	0.752	1.805		1.935	2.517	0.700	1.633	1.146	1.959	1.374	1.404	0.569
	P-value	0.747	0.245	0.708	0.050		0.033	0.005	0.760	0.086	0.329	0.030	0.183	0.168	0.875
ΔQdc	F	0.913	0.773	1.282	1.674	2.160		3.296	1.540	0.894	1.275	0.911	1.223	1.227	1.124
	P-value	0.543	0.687	0.234	0.076	0.016		0.000	0.113	0.562	0.238	0.544	0.272	0.269	0.346
ΔGdp	F	1.690	0.593	1.670	1.137	0.719	1.187		1.463	0.736	0.598	0.946	0.800	0.850	0.847
	P-value	0.072	0.855	0.077	0.336	0.741	0.297		0.142	0.724	0.851	0.509	0.659	0.607	0.611
$\Delta Psoy_{x,PR}$	F	0.578	0.605	0.952	1.291	0.769	1.293	0.826		1.652	0.886	1.935	1.227	1.050	1.230
	P-value	0.868	0.846	0.502	0.229	0.691	0.227	0.632		0.081	0.570	0.033	0.270	0.410	0.268
$\Delta Psoy_{d,PR}$	F	0.572	1.100	0.876	1.013	1.972	1.066	1.281	2.142		0.798	1.590	1.290	1.347	0.600
	P-value	0.872	0.367	0.580	0.444	0.029	0.396	0.234	0.017		0.661	0.098	0.229	0.197	0.850
$\Delta Psoy_{d,SP}$	F	0.987	1.543	1.181	1.089	1.179	1.137	1.058	2.383	2.402		0.823	2.431	1.490	1.026
	P-value	0.469	0.113	0.302	0.375	0.303	0.336	0.403	0.007	0.007		0.635	0.006	0.132	0.432
$\Delta Psoy_{d,RS}$	F	0.395	1.856	0.478	0.580	1.355	0.613	1.299	1.931	2.215	0.597		2.249	1.570	0.516
	P-value	0.969	0.043	0.933	0.866	0.192	0.839	0.223	0.033	0.013	0.853		0.011	0.104	0.911
$\Delta Psoy_{d,MT}$	F	0.763	1.089	1.011	1.899	1.090	1.948	1.681	1.901	0.633	0.824	1.117		0.902	0.641
	P-value	0.697	0.376	0.445	0.037	0.375	0.032	0.074	0.037	0.823	0.634	0.352		0.554	0.815
$\Delta Pmeal_{d,SP}$	F	2.064	1.702	1.672	1.724	1.021	1.829	1.916	2.131	1.951	1.622	1.796	2.681		0.864
	P-value	0.021	0.069	0.076	0.065	0.436	0.047	0.035	0.017	0.031	0.089	0.052	0.003		0.593
$\Delta Psoy_{oil}_{d,SP}$	F	1.049	1.163	1.595	1.255	1.529	1.307	0.858	1.925	2.597	2.167	2.122	2.969	2.110	
	P-value	0.411	0.316	0.096	0.251	0.117	0.219	0.599	0.034	0.003	0.015	0.018	0.001	0.018	

Source: prepared by the authors with RStudio 1.2.1578.

Table D4. Diagnostic tests for models of soybean complex

Test	Model									
	VAR(<i>p</i>)					VECM(<i>p</i> – 1)				
	SB1	SB2	SB3	SB4	SB5	SB1	SB2	SB3	SB4	SB5
Deterministic term: none										
Lags (<i>p</i>)	2	2	2	2	2	1	1	1	1	1
Q_{16}	241.690	237.350	251.210	238.360	247.220	244.510	238.450	251.720	241.520	248.290
Q_{16} (p-value)	0.199	0.258	0.102	0.243	0.137	0.216	0.304	0.135	0.257	0.170
<i>JB</i>	277.560	650.090	203.930	787.820	205.350	392.060	644.220	265.690	839.130	236.570
<i>JB</i> (p-value)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$MARCH_8$	827.060	842.300	842.440	816.530	845.650	822.410	836.440	842.710	820.690	847.890
$MARCH_8$ (p-value)	0.247	0.146	0.145	0.335	0.128	0.284	0.180	0.143	0.298	0.117
<i>OLS</i> – <i>CUSUM</i>	stable	stable	stable	stable	stable					
Deterministic term: constant										
Lags (<i>p</i>)	2	2	2	2	2	1	1	1	1	1
Q_{16}	238.930	232.050	245.200	232.270	242.130	243.600	237.690	250.680	239.900	247.270
Q_{16} (p-value)	0.235	0.342	0.158	0.338	0.193	0.228	0.316	0.145	0.281	0.182
<i>JB</i>	270.820	654.190	203.820	786.270	206.580	392.540	642.890	266.340	839.980	236.110
<i>JB</i> (p-value)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$MARCH_8$	829.030	808.390	818.620	787.600	837.610	822.300	836.550	842.730	820.820	847.830
$MARCH_8$ (p-value)	0.232	0.411	0.316	0.616	0.173	0.285	0.180	0.143	0.297	0.117
<i>OLS</i> – <i>CUSUM</i>	stable	stable	stable	stable	stable					
Deterministic term: trend										
Lags (<i>p</i>)	1	2	2	2	2		1	1	1	1
Q_{16}	269.200	229.340	242.990	229.700	236.440		236.930	249.080	241.620	242.870
Q_{16} (p-value)	0.095	0.389	0.183	0.383	0.271		0.329	0.161	0.256	0.238
<i>JB</i>	247.390	690.510	181.900	789.890	192.660		705.050	280.270	838.940	306.370
<i>JB</i> (p-value)	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000	0.000
$MARCH_8$	808.750	821.180	820.890	801.140	855.900		835.400	844.450	820.730	865.800
$MARCH_8$ (p-value)	0.407	0.294	0.297	0.482	0.083		0.187	0.134	0.298	0.053
<i>OLS</i> – <i>CUSUM</i>	stable	stable	stable	stable	stable					

Source: prepared by the authors with RStudio 1.2.1578.

Table D5. Diagnostic tests for models of blended diesel price

Test	Model									
	VAR(p)					VECM($p - 1$)				
	DC1	DC2	DC3	DC4	DC5	DC1	DC2	DC3	DC4	DC5
Deterministic term: none										
Lags (p)	3	2	2	2	2	2	1	1	1	1
Q_{16}	344.140	407.880	403.010	401.950	410.980	341.630	406.190	401.660	399.160	407.080
Q_{16} (p-value)	0.223	0.018	0.026	0.029	0.014	0.318	0.031	0.044	0.053	0.029
JB	728.380	1026.500	1010.100	1089.900	989.050	605.580	968.470	931.940	1034.600	927.860
JB (p-value)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$MARCH_5$	1873.600	1901.2	1928.700	1915.800	1900.000	1810.200	1892.300	1873.000	1928.700	1876.100
$MARCH_5$ (p-value)	0.111	0.048	0.018	0.029	0.050	0.428	0.064	0.113	0.018	0.104
$OLS - CUSUM$	stable	stable	stable	stable	stable					
Deterministic term: constant										
Lags (p)	3	2	2	2	2	2	1	1	1	1
Q_{16}	340.520	407.400	397.410	396.000	407.070	338.960	403.350	398.910	396.410	404.400
Q_{16} (p-value)	0.266	0.018	0.041	0.045	0.019	0.355	0.039	0.054	0.064	0.036
JB	610.550	984.010	965.900	1044.700	947.480	602.020	966.450	930.240	1034.000	925.990
JB (p-value)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$MARCH_5$	1801.600	1906.300	1800.000	1897.500	1904.000	1810.600	1893.700	1873.700	1929.600	1876.800
$MARCH_5$ (p-value)	0.485	0.040	0.019	0.054	0.043	0.426	0.061	0.111	0.017	0.102
$OLS - CUSUM$	stable	stable	stable	stable	stable					
Deterministic term: trend										
Lags (p)	3	2	2	3	2	2	1	1	2	1
Q_{16}	345.020	410.300	345.580	345.300	412.870	341.640	402.620	349.270	342.560	404.430
Q_{16} (p-value)	0.213	0.014	0.207	0.210	0.012	0.318	0.041	0.223	0.306	0.036
JB	660.960	966.950	767.390	807.970	932.510	605.070	961.950	699.340	777.800	937.240
JB (p-value)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
$MARCH_5$	1835.400	1885.400	1904.300	1848.300	1887.700	1810.600	1909.800	1862.000	1867.800	1890.600
$MARCH_5$ (p-value)	0.275	0.079	0.043	0.209	0.073	0.426	0.036	0.151	0.130	0.067
$OLS - CUSUM$	stable	stable	stable	stable	stable					

Source: prepared by the authors with RStudio 1.2.1578.

Table D6. Diagnostic tests for models of blended diesel demand

Test	Model		
	VAR(p)-D1	VECM($p-1$)-D1 $r = 1$	VECM($p-1$)-D1 $r = 2$
Deterministic term: none			
Lags (p)	2	1	1
Q_{16}	132.380	127.250	131.270
Q_{16} (p-value)	0.331	0.527	0.428
JB	252.460	271.780	279.130
JB (p-value)	0.000	0.000	0.000
$MARCH_8$	369.310	358.260	347.130
$MARCH_8$ (p-value)	0.001	0.003	0.010
$OLS - CUSUM$	instable		
Deterministic term: constant			
Lags (p)	4	3	3
Q_{16}	89.019	88.871	88.756
Q_{16} (p-value)	0.908	0.940	0.941
JB	171.200	178.870	182.260
JB (p-value)	0.000	0.000	0.000
$MARCH_8$	313.170	320.890	311.080
$MARCH_8$ (p-value)	0.148	0.089	0.167
$OLS - CUSUM$	stable		
Deterministic term: trend			
Lags (p)	4	3	3
Q_{16}	101.240	93.118	91.275
Q_{16} (p-value)	0.664	0.890	0.914
JB	193.540	180.480	172.750
JB (p-value)	0.000	0.000	0.000
$MARCH_8$	314.800	321.510	300.940
$MARCH_8$ (p-value)	0.133	0.085	0.288
$OLS - CUSUM$	stable		

Source: prepared by the authors with RStudio 1.2.1578.

Table D7. Cointegration tests for models of soybean complex

Hypotheses		Model																			
H_0	H_1	SB1				SB2				SB3				SB4				SB5			
		Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%
Trace																					
None																					
$r = 1$	$r > 1$	27.51		28.71	31.52	37.22	25.11		28.71	31.52	37.22	26.58		28.71	31.52	37.22	24.81		28.71	31.52	37.22
$r = 0$	$r > 0$	59.92	***	45.23	48.28	55.43	60.61	***	45.23	48.28	55.43	67.07	***	45.23	48.28	55.43	54.75	**	45.23	48.28	55.43
Constant																					
$r = 1$	$r > 1$	27.90		32	34.91	41.07	25.51		32	34.91	41.07	27.05		32	34.91	41.07	26.91		32	34.91	41.07
$r = 0$	$r > 0$	60.31	***	49.65	53.12	60.16	61.02	***	49.65	53.12	60.16	67.54	***	49.65	53.12	60.16	55.49	**	49.65	53.12	60.16
Trend																					
$r = 1$	$r > 1$						41.55	*	39.06	42.44	48.45	42.04	*	39.06	42.44	48.45	40.6	*	39.06	42.44	48.45
$r = 0$	$r > 0$						77.7	***	59.14	62.99	70.05	83.02	***	59.14	62.99	70.05	69.17	**	59.14	62.99	70.05
Maximum Eigenvalue																					
None																					
$r = 1$	$r = 2$	14.39		18.9	21.07	25.75	12.85		18.9	21.07	25.75	14.92		18.9	21.07	25.75	13.96		18.9	21.07	25.75
$r = 0$	$r = 1$	32.41	***	24.78	27.14	32.14	35.5	***	24.78	27.14	32.14	40.49	***	24.78	27.14	32.14	28.57	**	24.78	27.14	32.14
Constant																					
$r = 1$	$r = 2$	14.42		19.77	22	26.81	12.86		19.77	22	26.81	14.93		19.77	22	26.81	13.98		19.77	22	26.81
$r = 0$	$r = 1$	32.41	**	25.56	28.14	33.24	35.51	***	25.56	28.14	33.24	40.49	***	25.56	28.14	33.24	28.57	**	25.56	28.14	33.24
Trend																					
$r = 1$	$r = 2$						19.22		23.11	25.54	30.34	17.77		23.11	25.54	30.34	16.92		23.11	25.54	30.34
$r = 0$	$r = 1$						36.15	**	29.12	31.46	36.65	40.98	***	29.12	31.46	36.65	28.58		29.12	31.46	36.65

Source: prepared by the authors with RStudio 1.2.1578.

Note: critical values obtained from Osterwald-Lenum (1992).

Table D8. Cointegration tests for models of blended diesel price

Hypotheses		Model																			
H_0	H_1	DC1				DC2				DC3				DC4				DC5			
		Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%	Stat.	10%	5%	1%
Trace																					
None																					
$r = 1$	$r > 1$	35.4		45.23	48.28	55.43	38.2		45.23	48.28	55.43	38.57		45.23	48.28	55.43	38.67		45.23	48.28	55.43
$r = 0$	$r > 0$	68.79	*	66.49	70.6	78.87	72.08	**	66.49	70.6	78.87	75.7	**	66.49	70.6	78.87	75.41	**	66.49	70.6	78.87
Constant																					
$r = 1$	$r > 1$	37.21		49.65	53.12	60.16	39.73		49.65	53.12	60.16	40.1		49.65	53.12	60.16	40.35		49.65	53.12	60.16
$r = 0$	$r > 0$	70.69		71.86	76.07	84.45	73.64	*	71.86	76.07	84.45	77.25	**	71.86	76.07	84.45	77.13	**	71.86	76.07	84.45
Trend																					
$r = 1$	$r > 1$	54.29		59.14	62.99	70.05	53.77		59.14	62.99	70.05	56.14		59.14	62.99	70.05	53.11		59.14	62.99	70.05
$r = 0$	$r > 0$	87.69	**	83.2	87.31	96.58	90.3	**	83.2	87.31	96.58	92.13	**	83.2	87.31	96.58	90.51	**	83.2	87.31	96.58
Maximum Eigenvalue																					
None																					
$r = 1$	$r = 2$	15.19		24.78	27.14	32.14	16.13		24.78	27.14	32.14	16.01		24.78	27.14	32.14	16.42		24.78	27.14	32.14
$r = 0$	$r = 1$	33.4	**	30.84	33.32	38.78	33.88	**	30.84	33.32	38.78	37.14	**	30.84	33.32	38.78	36.73	**	30.84	33.32	38.78
Constant																					
$r = 1$	$r = 2$	15.31		25.56	28.14	33.24	16.19		25.56	28.14	33.24	16.09		25.56	28.14	33.24	16.51		25.56	28.14	33.24
$r = 0$	$r = 1$	33.48	*	31.66	34.4	39.79	33.91	*	31.66	34.4	39.79	37.15	**	31.66	34.4	39.79	36.78	**	31.66	34.4	39.79
Trend																					
$r = 1$	$r = 2$	23.49		29.12	31.46	36.65	22.14		29.12	31.46	36.65	23.04		29.12	31.46	36.65	21.94		29.12	31.46	36.65
$r = 0$	$r = 1$	33.4		34.75	37.52	42.36	36.53	*	34.75	37.52	42.36	35.99	*	34.75	37.52	42.36	37.4	*	34.75	37.52	42.36

Source: prepared by the authors with RStudio 1.2.1578.

Note: critical values obtained from Osterwald-Lenum (1992).

Table D9. Cointegration tests for models of blended diesel demand

Hypotheses		Model D1			
H_0	H_1	Stat.	10%	5%	1%
Trace					
None					
$r = 2$	$r > 2$	4.03	6.5	8.18	11.65
$r = 1$	$r > 1$	16.45 *	15.66	17.95	23.52
$r = 0$	$r > 0$	62.46 ***	28.71	31.52	37.22
Constant					
$r = 2$	$r > 2$	3.16	7.52	9.24	12.97
$r = 1$	$r > 1$	21.44 **	17.85	19.96	24.6
$r = 0$	$r > 0$	63.02 ***	32	34.91	41.07
Trend					
$r = 2$	$r > 2$	6.8	10.49	12.25	16.26
$r = 1$	$r > 1$	23.79 *	22.76	25.32	30.45
$r = 0$	$r > 0$	66 ***	39.06	42.44	48.45
Maximum Eigenvalue					
None					
$r = 2$	$r = 3$	4.03	6.5	8.18	11.65
$r = 1$	$r = 2$	12.41	12.91	14.9	19.19
$r = 0$	$r = 1$	46.01 ***	18.9	21.07	25.75
Constant					
$r = 2$	$r = 3$	3.16	7.52	9.24	12.97
$r = 1$	$r = 2$	18.27 **	13.75	15.67	20.2
$r = 0$	$r = 1$	41.59 ***	19.77	22	26.81
Trend					
$r = 2$	$r = 3$	6.8	10.49	12.25	16.26
$r = 1$	$r = 2$	16.99 *	16.85	18.96	23.65
$r = 0$	$r = 1$	42.2 ***	23.11	25.54	30.34

Source: prepared by the authors with RStudio 1.2.1578.

Note: critical values obtained from Osterwald-Lenum (1992).

Table D10. Cointegrating vector for blended diesel demand, alternative models

Vector	None		Constant		Trend	
	D1		D1		D1	
$\hat{\beta}$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_1$	$\hat{\beta}_2$
<i>Qdc</i>	1.000	0.000	1.000	0.000	1.000	0.000
<i>Pdc</i>	0.000	1.000	0.000	1.000	0.000	1.000
<i>Gdp</i>	-1.017 *** (-12.675)	1.069 *** (3.471)	-1.064 *** (4.430)	1.298 *** (4.430)	-1.078 *** (3.115)	1.280 *** (3.115)
<i>Constant</i>			-8.178 *** (-4.267)	-18.414 *** (-4.267)		
<i>Trend</i>					0.000 (-1.339)	-0.001 (-1.339)

Source: prepared by the authors with RStudio 1.2.1578.

Note: *t*-statistics in parentheses; the coefficients must be interpreted with inverted signals; *** significant at 1%; ** significant at 5%; * significant at 10%.

4. Fuel Policies in Brazil: Effects on Social Welfare and Greenhouse Gas Emissions

Abstract

In Brazil, the new pricing system of fossil fuels implemented in 2017 by Petrobras, the main oil company, and the biofuel policy called RenovaBio from 2017 transformed the fuel markets in the country. These policies plan to approximate the domestic fossil fuel prices to the international level and reduce the environmental damages from fuel consumption. This article aims to assess the effects of these new fuel policies in Brazil, measuring the impacts on social welfare and greenhouse gas (GHG) emissions. We construct a partial equilibrium model, including fuel and food markets such as gasoline, ethanol, biodiesel, diesel, other petroleum products, soybeans, and sugar. The proposed model permits to evaluate the impacts of fuel policies on prices, consumption, production, government revenue, producer and consumer surpluses, and GHG emissions in Brazil. We evaluate several scenarios. The *Status Quo** assumes current policies regarding fossil fuels and biofuels in Brazil, including an obligatory blend of 27% of anhydrous ethanol in pure gasoline, blend mandate of 7% of biodiesel in pure diesel, and taxes applied by the government. The First-Best scenario considers a competitive market with the inclusion of carbon tax imposed by the government on GHG emissions to abate the damages of pollution. Additionally, the RenovaBio scenario accounts for existing policies in the Brazilian fuel market and the inclusion of carbon credits supplied by biofuel producers and purchased by the fossil fuel industry. To calibrate the model, we use data of 2016 from several sources and elasticities reported by economic literature. The model outcomes for the *Status Quo** scenario are close to values observed in the Brazilian economy. The results of the First-Best policy present the highest surplus, there is a gain of 40.40% on welfare and a reduction of 11.49% in GHG emissions if compared to *Status Quo**. The RenovaBio scenario indicates a reduction of 7.06% in GHG emissions due to an expansion of biofuels consumption, while total welfare increases by 0.31%, representing a gain of R\$ 6.43 billion in the country. The RenovaBio policy is efficient because it expands the total welfare in the economy and decreases the level of GHG emissions, boosting the biofuel industry, and lowering the demand for fossil fuels.

Keywords: RenovaBio; Partial equilibrium model; Biofuel blend mandate; Consumer and producer surpluses; Deadweight loss.

4.1. Introduction

The Brazilian fuel sector experienced profound changes. The coexistence of fossil fuel and biofuel markets in a developing country is an important case of study. Since the 1950s, the government and Petróleo Brasileiro S.A. (Petrobras), a state-owned company, had a central role in the processes of decision-making and design of policies regarding the oil sector and its derivatives (Vieira Filho; Fishlow, 2017). In the middle 1970s, the biofuel industry, mainly of ethanol obtained from sugarcane, began to be structured because of the Brazilian need for fossil fuel substitution (Moraes; Zilberman, 2014).

In the 1990s, the monopoly of Petrobras in the oil industry was ruptured, and the ethanol market was deregulated (Brazil, 1997; Moraes; Zilberman, 2014). In the 2000s, the agenda regarding fuels in Brazil added factors that contributed to the expansion of biofuel and fossil fuel production and consumption, as the introduction of flex-fuel vehicles (FFV) and the discovery of new oil reserves, the called Pre-Salt reserves (Rodrigues; Bacchi, 2017; ANP, 2017). New laws and programs defined the choices of the Brazilian government regarding the fuel sector. In 2004, the biofuel industry was boosted by the National Biodiesel Production and Use Program (PNPB)²⁰, which in few years determined the mandatory blend of biodiesel in petroleum diesel (Pousa et al., 2007; Oliveira; Coelho, 2017).

In 2010, laws concerning the oil segment determined the functioning of the exploration rights system of Pre-Salt reserves, as well the spillovers of the petroleum revenues to society (Brazil, 2010a; 2010b; 2010c; ANP, 2017). In July 2017, Petrobras, which capped the price of gasoline A and diesel A (pure gasoline and regular diesel) for many years in Brazil, started exercising a new pricing policy for fossil fuels, letting the national prices follow the international prices. In December 2017, the government approved the National Biofuel Policy (RenovaBio), a policy aiming to expand biofuel production and contribute to reducing greenhouse gas (GHG) emissions.

According to Hira and Oliveira (2009), considering all technologies and renewable energy sources, biofuels are feasible substitutes for fossil fuels, the ethanol case in Brazil is a successful system that several developing countries could follow to decrease the dependence on petroleum. The Brazilian government policies enabled the progress of the ethanol industry, the country shows that it is possible to establish a path based on lower fossil fuel dependence. Furthermore, the emergence of the biodiesel industry in Brazil represents opportunities for future investments (Oliveira; Coelho, 2017).

²⁰ In Portuguese “Programa Nacional de Produção e Uso do Biodiesel”.

The literature highlights some private benefits of using fossil fuels and positive externalities of biofuel production and consumption. According to Hira and Oliveira (2009), there are advantages of utilizing crude oil as fuel, such as it is less corrosive to engines; there is more energy concentrated per unit; it has lower ignition temperature; and it generates many by-products, like plastics and fertilizers. However, the disadvantages are the higher emissions of toxic pollutants; the oil leak is threatening to the environment; it involves expressive investments on exploration and development; and, it requires widespread pipelines to transport.

In Brazil, ethanol from sugarcane is an advanced biofuel because it presents a lower carbon footprint among several raw agricultural materials used to produce this type of fuel (Moraes; Zilberman, 2014). Pousa et al. (2007) emphasize that biodiesel presents environmental and social favorable characteristics, it is (i) biodegradable; (ii) obtained from renewable resources; (iii) adequate to engines, with good lubrication and improving lifetime; (iv) harmless, with fewer pollutants from the combustion; and, (v) a good option for the vegetable oil industry. Oliveira and Coelho (2017) highlight that biodiesel is less toxic, the CO₂ emissions are reduced by 69.3% if compared to petroleum diesel, resulting in a smaller amount of air pollution. The benefits of using biofuels emphasized by the literature and the Brazilian government's concerns on the reduction of GHG emissions can be internalized by RenovaBio, a new fuel policy that creates a market of carbon credits issued by the biofuel producers and that states the purchase of these credits by the fossil fuel suppliers (Brazil, 2017).

In the fossil fuel market, Law No. 9,478 determines that Petrobras is no longer a monopolist in Brazil, but in practice, the market structure is still near to the monopoly case. There is a concentration of property rights in the exploration and production of oil. In the refinery level, in 2017, the Petrobras's market share was 98.64% (ANP, 2019a). These factors set Petrobras as a *de facto* monopoly, contributing significantly to price formation of fossil fuels in Brazil, since gasoline prices suffered slight variations, presenting a quasi-constant evolution at the refinery and pump level in the previous period of the new fossil fuel pricing policy. The recent adjustments of fossil fuel prices made by Petrobras expose that the previous pricing policy was not viable for the company's cash flow, because, in the past years, the firm needed to import gasoline with an international price greater than the price exercised at the national level (Moraes; Zilberman, 2014; Khanna et al., 2016; ANP, 2019b).

Therefore, this article intends to answer the following research questions: What are the effects of Petrobras's new pricing policy on consumer and producer surpluses? Is there evidence of deadweight loss due to fuel policies in Brazil? What are the impacts of the RenovaBio policy?

Are these policies contributing to reducing GHG emissions from the fuel sector in Brazil? Are the blend mandates of biofuels and fossil fuels decreasing GHG emissions in Brazil?

This paper aims to analyze the Brazilian policies concerning fossil fuels and biofuels, such as the *RenovaBio* policy and the new fossil fuel pricing system, evaluating the effects on social welfare and the level of GHG emissions. Moreover, there are three specific objectives: a) to study the effects of the biofuel blend mandates on fuel consumption, prices, production, and GHG emissions; b) to measure the consequences of the new pricing system of fossil fuels adopted by Petrobras on fuel prices, production, consumption, and emissions of GHG; c) to estimate the impacts of the *RenovaBio* policy on the level of GHG emissions, biofuel consumption, sugarcane and biodiesel industry surpluses, and fuel consumer surplus. For these purposes, this paper introduces the new agenda regarding fuel policies in Brazil and improves the partial equilibrium model proposed by Khanna et al. (2016), adding the blend mandate of diesel and biodiesel, the soybean market, and the costs and revenues of carbon credits.

4.2. Literature review: fuel market in Brazil

4.2.1. Crude oil and its derivatives

On October 3, 1953, Law No. 2004 established the *Petroleo Brasileiro S/A* (Petrobras) as a monopolist on the petroleum sector in Brazil concerning research, exploration, refining, and commercialization of oil derivatives. From the 1950s to the 1970s, Petrobras commanded the first activities in Research and Development (R&D) on oil production, resulting in the discovery of offshore oil in 1968 (Guaricema Field, Sergipe State). Since 1971, the Campos Basin²¹ was an important finding, enabling the development of offshore technologies. Additionally, the oil shocks in the 1970s contributed to the development of Proálcool and motivated the increase of investments in offshore production by Petrobras (Vieira Filho; Fishlow, 2017).

In the 1980s, Petrobras developed new equipment and know-how to exploit oil on the deep sea. From 1986 to 1991, the company invested in the Deep-water System Technological Innovation Program (Procap 1000), aiming to improve offshore technology to exploit oil at depths up to 1000 meters (m). Between 1993 and 1999, the Procap 2000 intended to extract oil up to 2000 m and, starting in 2000, Procap 3000 aimed to explore oil from ultra-deep waters, 3000 m. In 2012, it was created the Procap Visão Futuro, targeting to achieve production on the deep sea with lower costs (Ortiz Neto; Costa, 2007; Petrobras, 2018). As a result, Petrobras

²¹ The main oil fields in this Basin during the 1970s was Garoupa (1974), Pargo, Namorado and Badejo (1975), Enchova and Bicudo (1976) (Vieira Filho; Fishlow, 2017).

presents an important role in the research field regarding deep-water oil extraction and production, being granted with several international awards (Vieira Filho; Fishlow, 2017).

Through Law No. 9,478 from August 6, 1997, the called “Oil Law”, Petrobras was deposed from the monopoly in the oil sector in Brazil, being transferred to the Brazilian government the monopoly rights on research, extraction, refining, imports, exports, and bulk transportation. The “Oil Law” created the National Petroleum Agency (ANP), a regulatory agency regarding the oil industry, which on January 13, 2005, with Law No. 11,097 had its role amplified as overseer of biofuel sector (Brazil, 1997; 2005).

In 2007, with the use of offshore technologies, Petrobras discovered new oil reserves called Pre-Salt and located at the maritime area in the states of Santa Catarina, São Paulo, Rio de Janeiro, and Espírito Santo, covering 149 thousand km², one of the most important oil discoveries in recent years (ANP, 2017). In 2010, three important laws on the oil sector in Brazil were established: i) Law No. 12,351 (December 22, 2010) determined the production sharing regime in Pre-Salt reservoir and other strategic areas, and created a Social Fund; ii) Law No. 12,276 (June 6, 2010) granted onerously to Petrobras an area of 5 billion of barrels of oil equivalent (boe) from Pre-Salt for research and exploration, in return the government’s share on Petrobras increased; and iii) Law No. 12,304 (August 2, 2018) founded the Pré-Sal Petróleo S.A. (PPSA), a state company to represent the Brazilian government when Pre-Salt exploration and production occur as mixed regime, that is, as a consortium (Brazil, 2010a; 2010b; 2010c; ANP, 2017).

Therefore, there are three different periods in the Brazilian oil industry: First, the monopoly phase (1953-1997), which covered the exploration, refining, and bulk transport of oil, the policy goals were defined by the government through command-and-control regulations with a high level of protectionism. Second, the weakening of the monopoly (1998-2010), there was decentralized governance with public-private arrangements to improve competition. Third, the Pre-Salt oil production phase, which since 2010, Petrobras is a quasi-monopoly with public-private contracts. Petrobras is a multinational state-owned organization (public-private) that acts to implement government policies in Brazil (Aguiar; Freire, 2017).

Since 2007, Brazil became a net exporter of crude oil due to technologies and the discovery of Pre-Salt reserves. According to Figure 11a, between 2010 and 2017, the Brazilian crude oil production increased from 106.56 Million tons of oil equivalent (Mtoe) to 135.90 Mtoe (27.57%), the imports reduced from 17.51 Mtoe to 7.49 Mtoe (−57.23%) and the exports grew from 32.26 Mtoe to 53.88 Mtoe (65.02%). From the beginning of 2010 to June 2017, the productivity of Pre-Salt improved expressively, from 41 Thousand barrels per day (Mbbl/d) to 1.35 Million barrels

per day (MMbbl/d), exceeding the Post-Salt production of 1.32 MMbbl/d (ANP, 2017; PPSA, 2018). However, Brazil still needs to import oil derivatives. For the same period, the diesel production reduced 3.69% (35.13 to 33.83 Mtoe), consumption increased 6.51% (from 41.67 to 44.38 Mtoe), imports expanded 43.84% (from 7.64 to 10.99 Mtoe) and exports decreased 55.56% (from 1.31 to 0.58 Mtoe), as presented in Figure 11b. Considering 2010-2017, the gasoline production increased from 17.83 Mtoe to 21.82 Mtoe (22.37%), the consumption grew from 17.58 Mtoe to 24.86 Mtoe (41.40%) and imports from 0.39 Mtoe to 3.46 Mtoe (777.88%), while exports reduced 38.09%, from 0.59 Mtoe to 0.368 Mtoe (Figure 11c).

Figure 11. Brazilian consumption, production, exports, and imports of fuel from 1970 to 2017 (Million tons of oil equivalent - Mtoe)

Source: prepared by authors with data from EPE (2018).

4.2.2. Ethanol

In the early 1970s, Brazil was extremely dependent on oil imports. The first shock on oil prices caused by the Organization of the Petroleum Exporting Countries (OPEC) resulted in the first policy regarding alcohol in Brazil. On November 14, 1975, it was established the first phase (1975-1978) of the National Alcohol Program (Proálcool), which settled the use of alcohol blended with gasoline, reducing the imports of oil, saving foreign currency, improving the agricultural sector in the northeast region (important sugarcane and sugar producer) and increasing the demand for domestic agricultural and distillation machinery. In 1979, because of the second shock on oil prices due to the Iranian Revolution, the Brazilian government initiated the second phase of the alcohol program (1979-1985). In this period, the government stimulated the production of cars powered by alcohol, fixed ethanol price lower than gasoline price (capped at 65% of the gasoline price), offered credit for new sugarcane mills, and required adaptation of gas stations to make ethanol available for the population. Between 1985 and 1991, the drop in oil prices, the shortages of alcohol, and greater sugar prices led to the end of Proálcool (Hira; Oliveira, 2009; Vieira Filho; Fishlow, 2017).

The 1990s were characterized by the deregulation of the fuel sector. In 1997, the anhydrous and hydrous ethanol prices ceased to be fixed by the government and the gasoline prices were liberalized in 1998. In March 2003, the introduction of FFV, automobiles that can use ethanol and gasoline or different blends of both fuels, boosted again the ethanol industry, allowing consumers to choose the fuel according to price and energy efficiency (Hira; Oliveira, 2009). Additionally, the flex-fuel motorcycles were introduced in March 2009. According to Moraes and Zilberman (2014), in Brazil, these new technologies contributed to increasing the ethanol demand and changed the dynamic of the fuel market because the combustion of hydrous ethanol generates less energy. The hydrous ethanol is not economically attractive for consumers when its pump price is greater than 70% of the gasoline price. Therefore, the seasonal pattern of sugarcane harvest and weather conditions became important factors for fuel supply and demand in Brazil.

Figures 11d and 11e show historical data regarding the ethanol sector in Brazil. In the first phase of Proálcool (1975-1978), the anhydrous ethanol production increased 740.45% and hydrous 10.83%, while in the second phase (1979-1985) the production grew 35.11% and 1,497.53%, respectively. After the introduction of FFV, considering 2003-2017, the consumption of hydrous ethanol expanded 239.38% and anhydrous ethanol 65.27%. Since 1998, Brazil is a net exporter of hydrous ethanol, presenting a positive balance of 0.18 Mtoe in 2017. Regarding the

anhydrous ethanol, the country presented negative trade balances in 2011 and 2017, with net imports of 0.13 Mtoe and 0.43 Mtoe, respectively.

As a result of the deregulation process in Brazil in the 1990s, the sugar sector presented an expressive growth driven by exports and the reduction of ethanol consumption. Brazil has become the major sugar exporter, increasing its market share from approximately 5% in 1990/1991 to 50% in 2009/2010, where Asia and Africa were the main importers²². The mills capable of producing ethanol and sugar expanded, reducing the number of plants able to produce only ethanol or sugar (Moraes; Zilberman, 2014). According to CONAB (2019), in harvest 2016/2017, the main sugarcane producer state was São Paulo with 369.93 Million tons (Mtons) representing 56.29% of the national production with productivity of 77.50 tons per hectare (ton/ha). São Paulo State supplied 48.42% of the total ethanol in Brazil, summing 13.20 Million m³, where 46.61% was anhydrous ethanol and 53.39% was hydrous ethanol. Figure G1 and Table H3, in Appendices G and H, show the data regarding the Brazilian states.

4.2.3. Biodiesel

On October 22, 1980, the Brazilian government created the National Biodiesel Program (Proóleo) with Resolution No. 007. Proóleo was extinguished because of the drop in oil prices in the 1980s. On October 30, 2002, through Decree No. 702, it was launched an additional incentive regarding the biodiesel sector, the Brazilian Program of Technological Development for Biodiesel (ProBiodiesel) (Oliveira; Coelho, 2017). In December 2004, the Brazilian government established the National Biodiesel Production and Use Program (PNPB) aiming to make the production of biodiesel economically viable, contributing to the regional and social development in the northeast semiarid and Amazonian regions. The Law No. 11,097 (January 13, 2005) established the main raw materials such as vegetable oil and animal fats. To promote the sector, the government determined a reduction of tributes regarding biofuels based on Law No. 11,116 (May 18, 2005) and Decrees No. 5,297 (December 6, 2004) and No. 5,457 (June 6, 2005). To guarantee the social benefits, biodiesel producers who obtain raw materials from family agriculture (cooperatives registered in the National Program for the Strengthening of Family Farming - PRONAF²³) can receive a social fuel stamp, allowing fiscal exemptions and better credits conditions in public banks, as in the Brazilian Development Bank (BNDES²⁴). To ensure

²² According to Moraes and Zilberman (2014), the main importers of Brazilian sugar in this period were China, the United Arab Emirates, Algeria, Russia, Egypt, Indonesia, Saudi Arabia, and Nigeria.

²³ In Portuguese “Programa Nacional de Fortalecimento da Agricultura Familiar”.

²⁴ In Portuguese “Banco Nacional de Desenvolvimento Econômico e Social”.

the new biodiesel market, the ANP was responsible to conduct biodiesel auctions between biodiesel producers and Petrobras, being the last one in charge of purchasing biodiesel from producers with social fuel stamps. Additionally, it was created a research network to develop new technologies for the biodiesel industry (Pousa et al., 2007; Oliveira; Coelho, 2017).

The PNPB established mandatory blending percentages between petroleum diesel and pure biodiesel (B100, 100%). Between 2005 and 2007, the blending of 2% of biodiesel in fossil diesel (B2) was optional, but in October 2007, the B2 blend became obligatory, increasing to B4 (4%) in August 2009, B5 (5%) in March 2010 and B7 (7%) in February 2015 (Oliveira; Coelho, 2017; ANP, 2017). Law No. 13,263, from March 23, 2016, determined the periods of the beginning of new blend mandates: B8 (8%) in March 2017, B9 (9%) in March 2018, and B10 (10%) in March 2019. The Law No. 13,263 authorizes, given the technical tests, the increase of biodiesel blends up to 15% (B15) after 36 months of its sanction (Brazil, 2016). Figure 11f shows the evolution of the Brazilian biodiesel production. In 2006, during the non-mandatory B2 blending, the production was 0.054 Mtoe, achieving 3.01 Mtoe in 2016 when the obligatory blend was B7, a rise of 5,409.03%. In this period, due to the purchasing policy of Petrobras, the consumption of biodiesel followed the same path of production.

The raw materials used to produce biodiesel are divided into vegetable oils from soybean, cotton, peanut, canola, palm, sunflower, and castor bean; animal fats from cattle (beef tallow), fish and pork; and waste oils from the urban environment such as used cooking oil and other domestic and industrial residuals (Oliveira; Coelho, 2017). In Brazil, in 2017, the feedstocks used to produce biodiesel were soybeans (69.92%), beef tallow (13.64%), other fatty materials (10.40%), and pork fat (2.26%) (ANP, 2018).

Soybean is an important raw material for biodiesel production. In 2016, the major producing state was Mato Grosso (MT) with 30.51 Mtons, totaling 26.75% of the Brazilian production. In the same year, Paraná State (PR) was the second soybean producer with 17.17% (19.59 Mtons) and Rio Grande do Sul (RS) was placed in the third position with 16.40% (18.71 Mtons). The productivity was 3.27 ton/ha in Mato Grosso, 3.73 ton/ha in Paraná and 3.36 ton/ha in the Rio Grande do Sul (CONAB, 2019). According to ANP (2019a), in 2016, the Brazilian biodiesel industry was concentrated in the Rio Grande do Sul with 28.27% of the production (1.07 Million cubic meters (Mm³)), Mato Grosso with 21.54%, Goiás with 17.10% and Paraná with 10.33%. The data for all Brazilian states are in Figure G1 and Tables H1 and H2 (Appendices G and H).

4.3. Fuel policies in Brazil

4.3.1. Petrobras's new pricing policy

In June 2017, Petrobras established a new pricing system regarding the diesel and gasoline sold by its refineries. Since July 2017, the gasoline and diesel prices are adjusted more often, being monthly or even daily. This policy was discussed since October 2016, when the Executive Group of Market and Prices (GEMP²⁵) of Petrobras highlighted that the adjustments of prices in the pre-policy period were not sufficient to follow the increasing volatility of the Brazilian exchange rate (R\$/US\$) and the international prices of oil and derivatives (Petrobras, 2017). The new pricing system considers two factors (Petrobras, 2016): 1) the parity with the international market, considering freight rates of oil tanker, internal transport costs and port taxes; and 2) one margin to remunerate the risks concerning the production and commercialization such as exchange rate volatility, prices of port stays, taxes and profit. The fossil fuel prices will never be fixed below the international parity.

Figure 12 shows the evolution of fuel prices in R\$ per kilo oil equivalent (koe) and the blend mandates. During several years, the prices of pure gasoline (gasoline A) and diesel (diesel A) were capped by Petrobras's pricing policy. But after the implementation of the new pricing system of fossil fuels there was a change of pattern. Figure 12a shows that, in most of the period, the price of gasoline A in Brazil was higher than the price of gasoline in the United States (US), and the fluctuations of anhydrous ethanol price affect the price of gasoline C (gasohol, blend of anhydrous ethanol and gasoline A) at pump level.

²⁵ In Portuguese "Grupo Executivo de Mercado e Preços".

Figure 12. Fuel prices and blend mandates (Nov. 2002 - Jul. 2018)

Source: prepared by the authors with data from ANP (2019a), EIA (2019), and EPE (2018).

Figure 12b shows no clear relation between the changes in the international oil and diesel prices in Brazil until July 2017. The new fossil fuel pricing policy, the frequent currency

devaluation (R\$/US\$) and the reestablishment of the tax called Contribution for Intervention in the Economic Domain (CIDE²⁶) in 2015 contributed to rising diesel A price, causing a national strike of truck drivers at the beginning of 2018 (Oliveira; Coelho, 2017). The Brazilian biodiesel price (Figure 12b) is determined in auctions organized by ANP, being Petrobras the main buyer. The biodiesel was cheaper than diesel A in most of the period after March 2013. Additionally, the increase of diesel A prices and biodiesel blend mandate made the biodiesel industry attractive for new investments, resulting in the possibility of a reduction in diesel imports.

4.3.2. National Biofuel Policy (RenovaBio)

In December 2016, the Brazilian Ministry of Mines and Energy (MME) proposed a new policy regarding the biofuel sector, the National Biofuel Policy (RenovaBio). The design of the policy considered the proposals from the government and the production sector. The first document related to this policy was available for public consultation between February 2017 and March 2017. In July 2017, the National Energy Policy Council (CNPE²⁷) approved the directives and forwarded the plan as a bill for the approval of the Chamber of Deputies and the Brazilian Senate, which accepted it in November and December 2017, respectively (MME, 2019).

The Brazilian president, Michel Temer, sanctioned RenovaBio as Law No. 13,576 from December 26, 2017 (Brazil, 2017; 2018). There are four main objectives of RenovaBio: A) to contribute with the Brazilian commitment regarding The Paris Agreement on United Nations Framework Convention of Climate Change (UN, 2015); B) to increase the energy efficiency, reducing the GHG emissions in the biofuel sector; C) to expand the biofuel production and ensure the regularity of supply; and D) to improve the competition between different type of biofuel in the Brazilian fuel market (Brazil, 2017).

According to Brazil (2017), there are six policy instruments in the RenovaBio:

- 1) The target of reduction of GHG emissions: it considers a minimum of 10 years ahead from the establishment of RenovaBio;
- 2) Decarbonization Credits (CBIO): the primary issuance of CBIOs will be done in book-entry form, according to the volume of biofuel produced, imported, and commercialized by the primary issuing agent (producer or importer authorized by ANP). That is, the quantity of CBIO will be defined agreeing to the Energy and

²⁶ In Portuguese “Contribuição de Intervenção no Domínio Econômico”.

²⁷ In Portuguese “Conselho Nacional de Política Energética”.

Environmental Efficiency Rating (EEER), which will be established in the Biofuel Efficient Production Certificate (BEPC) from the issuing agent;

- 3) Biofuel Certification: the Biofuel Efficient Production Certificate will be granted to producers or importers that meet the requirements of efficiency improvement in productivity based on the life cycle²⁸. Thus, it will be compared the energy content and the GHG emissions of biofuels to fossil fuels;
- 4) A compulsory blend of biofuels and fossil fuels: according to Law No. 13,033 for gasoline A and anhydrous ethanol blend (27%) and Law No. 13,263 regarding the blend of biodiesel in petroleum diesel (7%) (Brazil, 2016).
- 5) Tax, financial and credit incentives;
- 6) Actions concerning The Paris Agreement on the United Nations Framework Convention on Climate Change.

Figure 13 shows the functional flow of RenovaBio. First, biofuel producers and importers request the Decarbonization Credits according to the volume produced, imported, or sold. Second, through the RenovaCalc is obtained the value of the life cycle of the product, which is used by the Inspection Company to evaluate the accordance with the EEER. Third, if the Energy and Environmental Efficiency Rating is at the required level, the producer or importer receives the Biofuel Efficient Production Certificate and, finally, can obtain the Decarbonization Credit. Fourth, the biofuel producers and importers use a bank or a financial institution (bookkeepers) to issue CBIOS in the stock market to be traded.

The fossil fuel suppliers (or distributors) need to compensate for GHG emissions caused by their products through the purchasing of CBIOS. The annual target (or quota) of GHG emissions allowed for each fossil fuel supplier is calculated in proportion to the market share concerning fossil fuel sales in the previous year. ANP has an important role in RenovaBio, the regulatory agency oversees the agents, documents, and actions: 1) the Inspection Company responsible for granting CBIOS to biofuel producers; 2) the Biofuel Efficient Production Certificate; 3) the primary issuers, producers and importers; and 4) the mandatory targets of individual compliance regarding fossil fuel suppliers (EPE, 2018).

²⁸ According to Brazil (2017), the life cycle considers the consecutive production stages of a productive chain, from the production of the raw material until the final deposition. Oliveira and Coelho (2017) emphasize that the life cycle assessment is a tool that enables quantifying the environmental effects regarding the use of energy and resources to produce a good, allowing to estimate the cumulative damage in the supply chain.

Figure 13. Chart of RenovaBio policy

Source: adapted from EPE (2018).

Note: ANP - National Agency of Petroleum, Natural Gas and Biofuels; CMBC - Biofuels and Fuels Monitoring Committee; CNPE - National Energy Policy Council; EPE - Energy Research Company (EPE).

4.4. Methodology

4.4.1. Model

The effects of fuel policies in Brazil are evaluated through a stylized partial equilibrium model. Khanna et al. (2016) developed a previous model that assumes an economy with a representative consumer who demands sugar, fuel (hydrous ethanol and gasohol), and other petroleum products using data from 2010/2011. In this model, Brazil is a price taker in the international oil market, since it exports a small share of this fuel in the world. The country is a price maker in the international market of sugar because it exports an expressive world share. The welfare regarding the sectors of fuel and sugar in the Brazilian economy is determined by the differences between the areas underneath the inverse demand and supply functions, considering taxes or subsidies, costs of production, and the anhydrous ethanol blend mandate. Based on policy scenarios and applying the Kuhn-Tucker conditions for an interior solution in the mathematical model, it is possible to determine the welfare, as well as the consumer surplus,

producer surplus, deadweight loss, prices, and the level of consumption, production, and net exports for all goods. In this paper, our modeling includes the soybeans market and biodiesel industry, as well as the blend mandate of biodiesel and pure diesel, and the RenovaBio policy.

An alternative structure can be defined to express the social welfare given the first-best amount of consumption of sugar, soybeans, pure gasoline, hydrous ethanol, and the level of marginal social damage due to GHG emissions. Supposing the absence of fuel taxes, subsidies, and blending mandates, it is possible to identify the socially optimal production and consumption, the level of GHG emissions generated from fuel utilization, and the government revenue when a carbon tax is applied.

After the first model proposed by Khanna et al. (2016), there were profound changes in the fuel market in Brazil, new policies regarding biofuels and fossil fuels were implemented. Therefore, this article purposes to incorporate the modifications in the Brazilian fuel policies using data from 2016, since this year is characterized as a pre-policy period. We aim to analyze the effects of the new pricing policy of fossil fuels and RenovaBio, assuming the blend mandate of biodiesel in diesel A (pure diesel) and the relationships with the soybeans sector. The new model includes the production, consumption, and net exports of soybeans, as well as the processing costs, prices, taxes, subsidies, and the level of emissions from the biodiesel industry. In Khanna et al. (2016), it was considered one case with a cap on fossil fuel prices due to the presence of Petrobras. In our model, we evaluate this scenario to compare with previous findings and estimate outcomes from the new fossil fuel pricing policy adopted in July 2017.

Figure 14 presents the graphical analysis of fuel policies in Brazil. We assume Brazil as price taker in the international oil market, as a consequence, it is a price taker in the gasoline and diesel markets (Figures 14a and 14f) since the country exports a small amount of these fuels in the world. Otherwise, Brazil is a price maker in the international market of sugar and soybeans (Figures 14e and 14j) because the country exports an expressive quantity worldwide. In 2016, the Brazilian market share in sugar exports was 56.77% and in soybean exports achieved 37.21%, as can be seen in Table H4 (Appendix H).

In Figure 14, ES_g represents the excess of supply of gasoline in Brazil, which is set at Q_{xog} , the export level, while ES_d is the excess of diesel in the country. With no government intervention, the domestic equilibrium level in gasoline, diesel, ethanol, and biodiesel are Q_{cgo} , Q_{cdo} , Q_{eo} , and Q_{bo} . The domestic consumption of sugar and soybeans are Q_{cso} and Q_{csbo} , respectively, while production levels are Q_{psso} and Q_{psbo} , and the exports are given by Q_{xso} and Q_{xsbo} .

Figure 14. Market of gasoline, ethanol, sugar, diesel, biodiesel, and soybean in Brazil

Source: prepared by the authors.

Figure 14. Market of gasoline, ethanol, sugar, diesel, biodiesel, and soybean in Brazil
Source: prepared by the authors.

Considering the blend mandate (m) of ethanol and gasoline, the gasoline demand rotates from D_g to D_{gm} and ethanol demand from D_e to D_{em} , since the obligatory blend is taken as an *ad valorem* tax on gasoline and compensation on ethanol consumption. The new consumption levels of gasoline and ethanol are set in Q_{gm} and Q_{em} , increasing prices to P_{gm} and P_{em} (Figures 14b and 14c). The mixture (m) of biodiesel and diesel rotates D_d to D_{dm} and D_b to D_{bm} , increasing the biodiesel consumption to Q_{bm} and reducing the diesel consumption to Q_{dm} . The prices rise to P_{dm} and P_{bm} (Figures 14g and 14h).

Additionally, the taxes (t) on gasoline and diesel decrease consumption to Q_{gmt} and Q_{dmt} and increase the ethanol and biodiesel consumption to Q_{emt} and Q_{bmt} . The demands shift downwards from D_{gm} to D_{gmt} for gasoline and upwards from D_{em} to D_{emt} for ethanol, and from D_{dm} to D_{dmt} and from D_{bm} to D_{bmt} for diesel and biodiesel, respectively. These movements increase gasoline price to P_{gmt} , ethanol to P_{emt} , diesel price to P_{dmt} , and biodiesel price to P_{bmt} . As a consequence, the level of gasoline and diesel exports increase to Q_{xgm} and Q_{xdm} with blends, and to Q_{xgmt} and Q_{xdmt} with taxes (Figure 14).

In Khanna et al. (2016), it was considered a scenario with a cap on fossil fuel prices affecting the gasoline price (P_{gc}) due to the presence of Petrobras. In our model, we contemplate this scenario to compare with the previous findings and evaluate the effects of the new pricing policy adopted in July 2017. The cap on fossil fuel prices shifts the ethanol demand down to D_{emtc} , establishing the consumption in Q_{emtc} and expanding the gasoline consumption to Q_{gmtc} (Figure 14).

If combined, the blend mandates and government taxes decrease the domestic supply of sugar from S_s to S_{smt} and, consequently, the international sugar supply from ES_s to ES_{smt} . The same movement is observed in the soybean market, reducing the domestic and international supplies to S_{sbmt} and ES_{sbmt} , and expanding prices to P_{sbmt} (Figure 14).

The new policies added to our model, RenovaBio and fossil fuel pricing system of Petrobras, present different results. With RenovaBio, it is expected that fossil fuel producers reduce supply to S_{gr} and S_{dr} , for example. These shifts are compensated with an increase of biofuel supply to S_{er} and S_{br} . The new consumption of ethanol will be higher than Q_{emt} , for example, Q_{er} , and the price of ethanol will range between P_{emt} and P_e . The new gasoline production level will be smaller than Q_{pgo} , being Q_{pgr} , and the consumption will be set between Q_{gmt} and Q_{cgo} . For biodiesel, the consumption will be greater than Q_{bmt} , for example, Q_{br} , but the price will remain between P_{bmt} and P_b . The diesel consumption will be higher than Q_{dmt} and

lesser than Q_{cdo} , while production is smaller than Q_{pdo} . The sugar sector will be affected by a reduction of the domestic supply to S_{sr} and the international supply to ES_{sr} . The domestic supply of soybean will decrease to S_{sbr} and the international supply to ES_{sbr} . Consequently, prices of sugar and soybean will rise to P_{sr} and P_{sbr} . On the other hand, the new pricing system of Petrobras eliminates the cap on gasoline and diesel prices, which is equivalent to the results of the case with blend mandate and taxes (mt).

Thus, given the complexity to determine the results of these different policies in the Brazilian fuel market, we propose a stylized partial equilibrium model to compute the effects on prices, production, consumption, exports, as well as the impacts on social welfare and GHG emissions.

4.4.2. Production and consumption for RenovaBio policy

Assuming a representative consumer that demands: ge = a set of goods composed by gasohol (blended gasoline called gasoline C) and ethanol; kb = a set of goods such as diesel C (blended diesel), biodiesel and other petroleum products; s = sugar; and sb = soybeans for food. The ge set has: g = gasoline A (pure gasoline); h = hydrous ethanol; and a = anhydrous ethanol. The kb set has: k = petroleum diesel A (pure diesel); b = biodiesel; and op = other petroleum products (fuel oil, LPG, naphtha, kerosene, and other oil products). Hydrous ethanol (h), anhydrous ethanol (a), sugar for domestic consumption (s^n), and sugar for exports (s^x) are obtained from sugarcane (sc) (39):

$$sc = \tau_a a + \tau_h h + \tau_s (s^n + s^x) \quad (39)$$

where, τ_a = technical coefficient regarding the sugarcane requirement per unit of anhydrous ethanol; τ_h = technical coefficient regarding the sugarcane requirement per unit of hydrous ethanol; τ_s = technical coefficient regarding the sugarcane requirement per unit of sugar. Ethanol (hydrous and anhydrous) and gasoline are substitutes, so φ_g is the ratio of the energy content of ethanol and gasoline, where $\varphi_g < 1$. In Brazil, the main raw material used to produce biodiesel is soybean (sb):

$$sb = \tau_{sb} b + sb^n + sb^x \quad (40)$$

where, τ_{sb} = technical coefficient regarding soybean requirement per unit of biodiesel; sb^n = domestic consumption of soybean for food; and sb^x = soybean exports. Petroleum diesel and biodiesel are complementary. The ratio of the energy content of biodiesel and diesel is $\varphi_k < 1$, and the ratio of the energy content of other petroleum products and diesel is φ_{op} .

As Brazil is a price taker in the international oil market, the oil price is set at p_o^w . Gasoline (g), petroleum diesel (k), and other petroleum products (op) are obtained from domestic oil production (o) and oil imports (o^x). The oil exports ($-o^x$) occur if there is an excess of national oil supply. Thus:

$$o = \gamma_g g + \gamma_k k + \gamma_{op} op + o^x \quad (41)$$

with, γ_g = conversion rate of gasoline to energy equivalent oil; γ_k = conversion rate of diesel to energy equivalent oil; γ_{op} = conversion rate of other petroleum products to energy equivalent oil. The inverse demand functions are downward sloping for ge , kb , s , and sb . Thus, the area underneath the demand functions of ge , kb , s , and sb are given by $\int_0^{ge} (\alpha_{ge} + \beta_{ge} ge) dge$, $\int_0^{kb} (\alpha_{kb} + \beta_{kb} kb) dkb$, $\int_0^{s^n} (\alpha_{s^n} + \beta_{s^n} s^n) ds^n$, $\int_0^{s^x} (\alpha_{s^x} + \beta_{s^x} s^x) ds^x$, $\int_0^{sb^n} (\alpha_{sb^n} + \beta_{sb^n} s^n) dsb^n$ and $\int_0^{sb^x} (\alpha_{sb^x} + \beta_{sb^x} sb^x) dsb^x$, where α are the intercepts and β are the slopes of demands (elasticities). The linear inverse supply functions are upward sloping. The area underneath of the oil supply function, $\int_0^o (\alpha_o + \beta_o o) do$, represents the cost of production of fossil fuels; the area underneath of the sugarcane supply function, $\int_0^{sc} (\alpha_{sc} + \beta_{sc} sc) dsc$, represents the cost of production of ethanol (anhydrous and hydrous) and sugar; and, the area underneath the soybean supply, $\int_0^{sb} (\alpha_{sb} + \beta_{sb} sb) dsb$, is the cost of biodiesel production and soybean for food. Where, α are the intercepts, and β are the supply elasticities.

Assuming Leontief technologies, the final products for consumption are obtained by the following costs: z_g = per unit cost of producing gasoline; z_k = per unit cost of producing diesel; z_{op} = per unit cost of producing other petroleum products; z_h = per unit cost of producing hydrous ethanol; z_a = per unit cost of producing anhydrous ethanol; z_b = per unit cost of producing biodiesel; z_s = per unit cost of producing sugar; and z_{sb} = per unit cost of producing soybeans. There are two blend mandates, one for gasoline and anhydrous ethanol and other for petroleum diesel and biodiesel, where θ is the mandatory percentage of anhydrous ethanol in

gasoline A, and ϕ is the mandatory percentage of biodiesel in petroleum diesel A. Therefore, $[(1 - \theta)/\theta]g = a$ and $[(1 - \phi)/\phi]k = b$.

The Brazilian government imposes taxes on fuels, and a cap on fossil fuel prices, as emphasized by Khanna et al. (2016). The cap is modeled as a subsidy on wholesale oil price consumed nationwide. Consequently, t^g = tax on gasoline; t^k = tax on diesel; t^{op} = tax on other petroleum products; t^h = tax on hydrous ethanol; t^a = tax on anhydrous ethanol; t^b = tax on biodiesel; and, t^o = subsidy on wholesale oil price. The RenovaBio policy is accounted as an additional revenue for biofuel producers (biodiesel, hydrous and anhydrous ethanol), and an extra cost for fossil fuel producers (gasoline, diesel, and other petroleum products). If p^{cbio} is the price of Carbon Credits (CBIOs), r^{cbio} is the revenue of CBIOs, and c^{cbio} is the cost of CBIOs. Hence, $r^{cbio} = p^{cbio}(h + a + b)$ and $c^{cbio} = p^{cbio}(g + k + op)$. Assuming that the consumer surplus for all goods is additive, market-clearing conditions, and non-negativity, we determine that the choice between fuels, sugar, and soybean is given by the following social welfare problem:

$$\begin{aligned}
 \max_{g,k,op,a,h,b,s^n,s^x,sb^n,sb^x,o^x} & \int_0^{ge} (\alpha_{ge} + \beta_{ge}ge) dge + \int_0^{kb} (\alpha_{kb} + \beta_{kb}kb) dkb \\
 & + \int_0^{s^n} (\alpha_{s^n} + \beta_{s^n}s^n) ds^n + \int_0^{s^x} (\alpha_{s^x} + \beta_{s^x}s^x) ds^x \\
 & + \int_0^{sb^n} (\alpha_{sb^n} + \beta_{sb^n}sb^n) dsb^n + \int_0^{sb^x} (\alpha_{sb^x} + \beta_{sb^x}sb^x) dsb^x \\
 & + \overline{p_o}^w o^x + t^o(\gamma_g g + \gamma_k k + \gamma_{op} op) - \int_0^o (\alpha_o + \beta_o o) do \\
 & - \int_0^{sc} (\alpha_{sc} + \beta_{sc}sc) dsc - \int_0^{sb} (\alpha_{sb} + \beta_{sb}sb) dsb - z_g g - z_k k \\
 & - z_{op} op - z_h h - z_a a - z_b b - z_s(s^n + s^x) - z_{sb}(sb^n + sb^x) \\
 & - t^g g - t^k k - t^{op} op - t^h h - t^a a - t^b b - p^{cbio}(g + k + op) \\
 & + p^{cbio}(h + a + b)
 \end{aligned} \tag{42}$$

Subject to:

$$ge = g + \varphi_g h + \varphi_g a \tag{43}$$

$$kb = k + \varphi_k b + \varphi_{op} op \tag{44}$$

$$sc = \tau_a a + \tau_h h + \tau_s (s^n + s^x) \quad (45)$$

$$sb = \tau_{sb} b + sb^n + sb^x \quad (46)$$

$$o = \gamma_g g + \gamma_k k + \gamma_{op} op + o^x \quad (47)$$

$$[(1 - \theta)/\theta]g = a \quad (48)$$

$$[(1 - \phi)/\phi]k = b \quad (49)$$

The Lagrangian is given by:

$$\begin{aligned} L_1 = & \int_0^{g+\varphi_g h+\varphi_g a} (\alpha_{ge} + \beta_{ge} ge) dge + \int_0^{k+\varphi_k b+\varphi_{op} op} (\alpha_{kb} + \beta_{kb} kb) dkb \quad (50) \\ & + \int_0^{s^n} (\alpha_{s^n} + \beta_{s^n} s^n) ds^n + \int_0^{s^x} (\alpha_{s^x} + \beta_{s^x} s^x) ds^x \\ & + \int_0^{sb^n} (\alpha_{sb^n} + \beta_{sb^n} sb^n) dsb^n + \int_0^{sb^x} (\alpha_{sb^x} + \beta_{sb^x} sb^x) dsb^x \\ & + p_o^w o^x + t^o (\gamma_g g + \gamma_k k + \gamma_{op} op) \\ & - \int_0^{\gamma_g g + \gamma_k k + \gamma_{op} op + o^x} (\alpha_o + \beta_o o) do \\ & - \int_0^{\tau_a a + \tau_h h + \tau_s (s^n + s^x)} (\alpha_{sc} + \beta_{sc} sc) dsc \\ & - \int_0^{\tau_{sb} b + sb^n + sb^x} (\alpha_{sb} + \beta_{sb} sb) dsb - z_g g - z_k k - z_{op} op - z_h h \\ & - z_a a - z_b b - z_s (s^n + s^x) - z_{sb} (sb^n + sb^x) - t^g g - t^k k \\ & - t^{op} op - t^h h - t^a a - t^b b - p^{cbio} (g + k + op) \\ & + p^{cbio} (h + a + b) + \lambda_g \left[\frac{1 - \theta}{\theta} g - a \right] + \lambda_k \left[\frac{1 - \phi}{\phi} k - b \right] \end{aligned}$$

where, $\lambda_g > 0$ is the shadow price of the blend mandate of anhydrous ethanol and gasoline A, and $\lambda_k > 0$ is the shadow price of the obligatory mixture of biodiesel and diesel A. Using Kuhn-Tucker conditions with an interior solution, we can obtain the partial derivatives of L_1 and the main functions regarding the prices. Appendix E presents the mathematical results and the main relationships between prices and quantities considering the level of consumption and production under the fuel policies in Brazil.

4.4.3. Socially optimal production and consumption (First-Best)

In the First-Best policy, the level of consumption of sugar, soybeans, and fuel is obtained according to the following assumptions: i) Brazil has market power in the international sugar market to set the price; ii) Brazil has market power to set soybean price in the international market; iii) the cap on fossil fuel price is removed, that is, the implicit subsidy on oil is zero; iv) there is no blending mandate between ethanol and gasoline, resulting in no need for anhydrous ethanol, the market commercializes only hydrous ethanol; v) there is no blending mandate between biodiesel and pure diesel; vi) there are no taxes on fuels; and, vii) the RenovaBio policy is not applied.

To account for the effects of negative externalities, we add the marginal social damage caused by greenhouse gas emissions and the level of emissions per unit and type of fuel: σ_o = GHG emissions per unit of oil; σ_h = GHG emissions per unit of hydrous ethanol; σ_{sb} = GHG emissions per unit of soybean; σ_s = GHG emissions per unit of sugar; ε^m = marginal social damage due to GHG emissions. The coefficients σ_h and σ_s account for GHG emissions from sugarcane cultivation, and σ_{sb} considers the emissions from soybean production. The aggregate level of GHG emissions from consumption is $\sigma_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) + \sigma_h h + \sigma_s(s^n + s^x) + \sigma_{sb}(sb^n + sb^x)$. The Lagrangian (L_2) of the social planner is:

$$\begin{aligned}
 L_2 = & \int_0^{g+\varphi_g h} (\alpha_{ge} + \beta_{ge} ge) dge + \int_0^{k+\varphi_{op} op} (\alpha_{kb} + \beta_{kb} kb) dkb \\
 & + \int_0^{s^n} (\alpha_{s^n} + \beta_{s^n} s^n) ds^n + \int_0^{s^x} (\alpha_{s^x} + \beta_{s^x} s^x) ds^x \\
 & + \int_0^{sb^n} (\alpha_{sb^n} + \beta_{sb^n} sb^n) dsb^n + \int_0^{sb^x} (\alpha_{sb^x} + \beta_{sb^x} sb^x) dsb^x \\
 & + p_o^w o^x - \int_0^{\gamma_g g + \gamma_k k + \gamma_{op} op + o^x} (\alpha_o + \beta_o o) do \\
 & - \int_0^{\tau_h h + \tau_s(s^n + s^x)} (\alpha_{sc} + \beta_{sc} sc) dsc - \int_0^{sb^n + sb^x} (\alpha_{sb} + \beta_{sb} sb) dsb \\
 & - z_g g - z_k k - z_{op} op - z_h h - z_s(s^n + s^x) - z_{sb}(sb^n + sb^x) \\
 & - \varepsilon^m [\sigma_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) + \sigma_h h + \sigma_s(s^n + s^x) \\
 & + \sigma_{sb}(sb^n + sb^x)]
 \end{aligned} \tag{51}$$

Using Khun-Tucker conditions for an interior solution, we can obtain the partial derivatives of L_2 , and how the carbon tax can influence prices, production, and consumption. Appendix E presents the mathematical results for the First-Best scenario.

4.4.4. Scenarios and data

The model allows evaluating different policies for fossil fuels and biofuels in Brazil, combining or relaxing some assumptions. Table 23 summarizes the scenarios.

Table 23. Scenarios

Scenario	Description	Govern- ment taxes	E27 blend	B7 blend	Cap on fossil fuels	Carbon tax on GHG emissions	Carbon Credits (CBIOS)
No Policy	No government intervention. There are no government taxes, blend mandates, carbon taxes, and carbon credits.						
Government Taxes+E27	Accounts for government taxes and an obligatory blend of 27% of anhydrous ethanol in gasoline A (pure gasoline).	X	X				
Government Taxes+B7	Accounts for government taxes and an obligatory blend of 7% of biodiesel in diesel A (pure diesel).	X		X			
Government Taxes	Taxes applied by the government on biofuels and fossil fuels.	X					
<i>Status Quo</i> *+Cap	Considers an obligatory blend of 27% of anhydrous ethanol in gasoline A (pure gasoline), an obligatory blend of 7% of biodiesel in diesel A (pure diesel), taxes applied by the government, and a cap on fossil fuel prices of R\$ 0.22 per koe.	X	X	X	X		
<i>Status Quo</i> *	Current policies of 2016: an obligatory blend of 27% of anhydrous ethanol in gasoline A (pure gasoline), an obligatory blend of 7% of biodiesel in diesel A (pure diesel), and taxes applied by the government.	X	X	X			
First-Best	A carbon tax of US\$ 31.2/ton CO _{2e} (R\$ 101.67) is applied by the government.					X	
<i>Status Quo</i> *+Carbon Tax	Policies of 2016 and a carbon tax imposed by the government. The carbon tax ranges from US\$ 31.20/ton CO _{2e} (R\$ 101.67) to US\$ 93.60/ton CO _{2e} (R\$ 305.00).	X	X	X		X	
<i>Status Quo</i> *+RenovaBio	Incorporates an additional cost regarding Carbon Credits (CBIOS) for fossil fuel producers and extra revenue of CBIOS for biofuel suppliers. It is considered several prices for CBIOS ranging between R\$ 0.05 and R\$ 0.50 per koe.	X	X	X			X

Source: prepared by the authors.

Note: X represents the inclusion of a specific policy in the model.

In the No Policy scenario, there is no government intervention such as blend mandates and taxes. The scenarios with blend E27 or B7 consider the obligatory mixtures of biofuels and fossil fuels, and government taxes. In the Government Taxes case, we calculate the effects of taxes applied on prices by the Brazilian government with no obligatory blend. The *Status Quo**+Cap adds a subsidy on domestic fossil fuel prices considering an average cap regarding the period of 2002-2012, as applied by Khanna et al. (2016). The value of oil cap was deflated to R\$ of 2016 according to the General Price Index - Domestic Availability (IGP-DI)²⁹, which represents R\$ 0.22 per koe of fossil fuel³⁰. The *Status Quo** scenario considers government taxes, the blend of 27% of anhydrous ethanol in pure gasoline, and 7% of biodiesel in petroleum diesel.

The First-Best scenario assumes no obligatory blend and no taxes on fuels, but it accounts for a carbon tax applied by the government considering the GHG emissions intensity of each type of fuel in the model. In this scenario, the government aims to reduce environmental damages through a carbon tax. The tax applied is US\$ 31.20 (R\$ 101.67) per ton of carbon dioxide equivalent (ton CO₂e). This value was obtained in Nordhaus (2017), used in the DICE-2016R model.

The *Status Quo**+Carbon Tax combines government taxes, blends mandates, and carbon tax ranging from US\$ 31.20/ton CO₂e to US\$ 93.60/ton CO₂e (R\$ 101.67 - R\$ 305.00). The maximum value of US\$ 93.60/ton CO₂e represents three times the value adopted by Nordhaus (2017). According to the report of the World Bank (2019) regarding the existing carbon pricing initiatives in the world in 2016, our upper limit of carbon tax is close to values in Switzerland (US\$ 86.19/ton CO₂e) and below the standards applied in Sweden (US\$ 130.50/ton CO₂e), as can be seen in Table F4 (Appendix F). The *Status Quo**+RenovaBio policy is the *Status Quo** scenario including an extra cost of Carbon Credits (CBIOs) for fossil fuel producers and additional revenue from CBIOs for biofuel suppliers. The price of CBIOs vary between R\$ 0.05 and R\$ 0.50 per koe.

The mathematical model is constructed as a code in the software General Algebraic Modeling System (GAMS) version 25.1.3. The data to calibrate the model in GAMS concerns the year of 2016. The demand and supply elasticities were obtained from the literature, as can be seen in Table F1 (Appendix F). The data on production, consumption, exports, imports, and technical coefficients regarding different sectors in Brazil were obtained from several sources (Table F2),

²⁹ In Portuguese “Índice Geral de Preços - Disponibilidade Interna”, where August 1994 is equal to 100 (FGV, 2019).

³⁰ In Khanna et al. (2016), the cap on fossil fuel prices was set at R\$ 0.18 per koe (R\$ 0.22 per koe in R\$ of 2016), which represents the average difference between the Brazilian and international prices of gasoline between 2002 and 2012.

as well as the energy intensity and coefficients of GHG emissions (Table F3), as shown in Appendix F.

4.5. Results

Table 24 shows the model validation comparing *Status Quo** results of endogenous price and quantity to values observed in 2016. The differences between observed values of 2016 and model results are less than 10%. Regarding oil production, the error is equal to zero. For soybean cultivation is 1.66%, for sugar production, the difference is 3.30%, and for sugarcane, the variation is 5.68%.

Table 24. Model validation

Variable	Observed in 2016	<i>Status Quo*</i> Policy	Difference
Production			
Oil (Mtoe)	130.37	130.37	0.00%
Sugarcane (Mtons)	651.50	688.53	5.68%
Sugar (Mtons)	38.72	40.00	3.30%
Soybean (Mtons)	114.60	116.50	1.66%
Consumption			
Hydrous ethanol (Mtoe)	8.32	8.28	-0.41%
Anhydrous ethanol (Mtoe)	6.01	5.71	-5.09%
Total ethanol (Mtoe)	14.33	13.99	-2.38%
Biodiesel (Mtoe)	3.01	3.11	3.24%
Gasoline (Mtoe)	24.23	22.98	-5.15%
Diesel and other petroleum products (Mtoe)	78.53	80.86	2.96%
Prices			
Domestic sugar (R\$/ton)	976.50	915.42	-6.25%
Domestic soybean (R\$/ton)	1290.50	1238.11	-4.06%
Gasohol (E27) - consumer level (R\$/koe)	2.78	2.93	5.17%
Diesel B7 - consumer level (R\$/koe)	2.60	2.51	-3.33%

Source: prepared by the authors with GAMS version 25.1.3.

Note: *Status Quo** Policy includes fuel taxes and blend mandates.

Concerning the consumption level, the differences between the values of 2016 and model outcomes are small. For total ethanol (hydrous and anhydrous ethanol) the error is -2.38% , and for diesel and other petroleum products, it achieves 2.96% . The predicted prices are close to the market level in 2016 since the highest alteration is observed for domestic sugar (6.25%), and the smallest for Diesel B7 at the consumer level (-3.33%) (Table 24). Therefore, the chosen elasticities for supply and demand present a good approximation of market conditions in Brazil.

Table 25 shows the effects of different policies in the Brazilian fuel market. The baseline is the No Policy scenario (*a*), it shows the prices, quantities, and the level of GHG emissions with no government intervention, where anhydrous ethanol and biodiesel consumption are equal to zero because there is no mandatory blend. The consumption of hydrous ethanol is 4.33 Mtoe, showing that with no incentive, there is still renewable fuel demand, but gasoline and diesel consumption are large, 39.09 Mtoe and 89.71 Mtoe, respectively. Consequently, the level of

GHG emissions is 440.71 Mton of CO₂e, representing damage of R\$ 44.80 billion. Without taxes or subsidies imposed, there is no government revenue or expense.

The government taxes and the blend mandated of anhydrous ethanol in pure gasoline, scenario (b), results in an increase of sugarcane production in 42.11% if compared to No Policy (a). The use of anhydrous ethanol increases to 6.44 Mtoe, while gasoline consumption reduces 33.71% (−13.18 Mtoe). As a result, the domestic and international prices of sugar increase 91.47% both, because the E27 blend causes less sugar production (−2.58%). The level of GHG emissions reduces by 9.81% if compared to the baseline, demonstrating that this policy decreases the damages of pollution. In scenario (c), the blend of biodiesel in pure diesel (B7) also abates the level of GHG emissions, −8.84%, because there is larger use of a clearer fuel, +3.15 Mtoe of biodiesel, lessening pure diesel consumption (−8.61%) since both fuels are complementary. But, soybean prices for food in the international and national markets increase by 79.17%, even with the rise of soybean production of 18.98%.

When the government applies taxes on fuels, scenario (d), the consumption of pure gasoline decreases 33.60% and diesel 3.25%, while the hydrous ethanol demand increases from 4.33 Mtoe to 12.10 Mtoe (179.49%). The price of sugar rises 91.36%, achieving R\$ 821.24 per ton. The taxes result in two important effects. First, a government revenue of R\$ 99.97 billion. Second, a reduction of GHG emissions damage from R\$ 44.80 billion in No Policy (a) to R\$ 39.49 billion (−11.87%).

The cap on oil is modeled as a subsidy on domestic fossil fuel prices considering an average cap regarding the period of 2002-2012, as applied by Khanna et al. (2016), which represents R\$ 0.22 per koe. The cap on fossil fuels aims to reduce fuel prices for consumers. This policy was adopted by the Brazilian government for many years as an instrument to control costs and, consequently, the level of prices in the economy. Following the method applied by Khanna et al. (2016) with updated data, we observed that the Brazilian pure gasoline price was greater than the international level. The average gap considering the period of 2003-2016 is about R\$ 0.29 per koe, there is a margin applied by importers and domestic refineries. Thus, we evaluated *Status Quo** (f) applying this margin of R\$ 0.29 per koe on fossil fuels, and *Status Quo*+Cap* (e) discounting R\$ 0.22 per koe due to cap policy, which results in a net margin of R\$ 0.07 per koe.

Table 25. Results I

Variables	No Policy	Government Taxes+E27		Government Taxes+B7		Government Taxes		Status Quo*+Cap		Status Quo*	
	(a)	(b)	(b-a)/a	(c)	(c-a)/a	(d)	(d-a)/a	(e)	(e-a)/a	(f)	(f-a)/a
Prices											
Domestic sugar (R\$/ton)	429.16	821.70	91.47%	821.24	91.36%	821.24	91.36%	844.24	96.7%	915.42	113.31%
International sugar (R\$/ton)	429.16	821.70	91.47%	821.24	91.36%	821.24	91.36%	844.24	96.7%	915.42	113.31%
Domestic soybean (R\$/ton)	695.28	695.28	0.00%	1245.71	79.17%	695.28	0.00%	1243.88	78.9%	1238.11	78.07%
International soybean (R\$/ton)	695.28	695.28	0.00%	1245.71	79.17%	695.28	0.00%	1243.88	78.9%	1238.11	78.07%
Hydrous - producer (R\$/koe)	1.19	2.41	102.22%	2.41	102.10%	2.41	102.10%	2.48	108.1%	2.70	126.62%
Hydrous - consumer (R\$/koe)	1.19	2.63	121.19%	2.63	121.07%	2.63	121.07%	2.70	127.1%	2.93	145.60%
Gasoline - producer (R\$/koe)	1.19	1.19	0.00%	1.19	0.00%	1.19	0.00%	1.19	0.0%	1.19	0.00%
Gasoline - consumer (R\$/koe)	1.19	2.63	121.19%	2.63	121.07%	2.63	121.07%	2.70	127.1%	2.93	145.60%
Gasohol - consumer (R\$/koe)	1.19	2.63	121.19%	2.63	121.07%	2.63	121.07%	2.70	127.1%	2.93	145.60%
Diesel - producer (R\$/koe)	1.15	1.15	0.00%	1.15	0.00%	1.15	0.00%	1.15	0.0%	1.15	0.00%
Diesel - consumer (R\$/koe)	1.15	1.84	59.71%	2.24	93.71%	1.84	59.71%	2.30	99.5%	2.51	117.79%
Diesel B7 - consumer (R\$/koe)	1.15	1.84	59.71%	2.24	93.71%	1.84	59.71%	2.30	99.5%	2.51	117.79%
Other petroleum prod. - producer (R\$/koe)	1.15	1.84	59.71%	2.24	93.71%	1.84	59.71%	2.23	93.4%	2.22	92.57%
Other petroleum prod. - consumer (R\$/koe)	1.15	1.84	59.71%	2.24	93.71%	1.84	59.71%	2.30	99.5%	2.51	117.79%
Production											
Sugarcane (Mtons)	452.47	643.03	42.11%	642.81	42.07%	642.81	42.07%	653.98	44.5%	688.53	52.17%
Sugar (Mtons)	41.32	40.26	-2.58%	40.26	-2.58%	40.26	-2.58%	40.19	-2.7%	40.00	-3.20%
Soybean (Mtons)	98.13	98.13	0.00%	116.76	18.98%	98.13	0.00%	116.70	18.9%	116.50	18.72%
Oil (Mtoe)	130.37	130.37	0.00%	130.37	0.00%	130.37	0.00%	130.37	0.0%	130.37	0.00%
Consumption											
Hydrous ethanol (Mtoe)	4.33	5.70	31.67%	12.10	179.49%	12.10	179.49%	6.32	46.0%	8.28	91.34%
Anhydrous ethanol (Mtoe)	0.00	6.44	6.44%	0.00	0.00%	0.00	0.00%	6.26	6.3%	5.71	5.71%
Total ethanol (Mtoe)	4.33	12.14	180.38%	12.10	179.49%	12.10	179.49%	12.58	190.7%	13.99	223.21%
Biodiesel (Mtoe)	0.00	0.00	0.00%	3.15	3.15%	0.00	0.00%	3.14	3.1%	3.11	3.11%
Gasoline (Mtoe)	39.09	25.91	-33.71%	25.96	-33.60%	25.96	-33.60%	25.21	-35.5%	22.98	-41.22%
Diesel and other petroleum products (Mtoe)	89.71	86.80	-3.25%	81.99	-8.61%	86.80	-3.25%	81.72	-8.9%	80.86	-9.87%
Exports											
Sugar (Mtons)	30.60	29.66	-3.09%	29.66	-3.08%	29.66	-3.08%	29.60	-3.3%	29.43	-3.82%
Soybean (Mtons)	76.50	76.50	0.00%	69.73	-8.84%	76.50	0.00%	69.76	-8.8%	69.83	-8.72%
Oil (Mtoe)	1.57	17.66	1022.33%	22.43	1325.08%	17.62	1019.53%	23.45	1390.0%	26.54	1586.22%
Consumer surplus											
Gasohol and ethanol (B R\$)	253.41	154.51	-39.03%	154.51	-39.03%	154.51	-39.03%	152.77	-39.7%	147.42	-41.83%
Diesel B7 and other petroleum prod. (B R\$)	951.96	831.35	-12.67%	800.56	-15.90%	831.35	-12.67%	795.07	-16.5%	777.86	-18.29%
Sugar (B R\$)	183.44	179.26	-2.28%	179.26	-2.28%	179.26	-2.28%	179.02	-2.4%	178.27	-2.82%
Soybean (B R\$)	93.68	93.68	0.00%	82.15	-12.31%	93.68	0.00%	82.19	-12.3%	82.30	-12.14%
Producer surplus											
Oil industry (B R\$)	71.16	71.16	0.00%	71.16	0.00%	71.16	0.00%	86.13	21.0%	131.59	84.92%
Sugarcane industry (B R\$)	211.92	260.47	22.91%	260.40	22.88%	260.40	22.88%	264.10	24.6%	276.14	30.30%
Soybean industry (B R\$)	366.35	366.35	0.00%	462.46	26.24%	366.35	0.00%	462.08	26.1%	460.90	25.81%
Government revenue (B R\$)	0.00	99.91	99.91%	97.02	97.02%	99.97	99.97%	95.86	95.9%	92.37	92.37%
GHG emissions damage (B R\$)	44.80	40.41	-9.81%	40.84	-8.84%	39.49	-11.87%	44.50	-0.7%	44.14	-1.49%
GHG emissions (Mtons CO ₂ e)	440.71	397.49	-9.81%	401.75	-8.84%	388.40	-11.87%	437.69	-0.7%	434.14	-1.49%
Total surplus (B R\$)	2087.12	2016.28	-3.39%	2066.68	-0.98%	2017.19	-3.35%	2072.72	-0.69%	2102.70	0.75%

Source: prepared by the authors with GAMS version 25.1.3.

Note: deviations are evaluated relative to No Policy, column (a); Status Quo* policy includes government fuel taxes and blend mandates.

The differences between No Policy and *Status Quo** are huge, the gasohol price is 145.60% higher, while pure gasoline consumption is 41.22% smaller due to the obligatory blend of anhydrous ethanol in gasoline. The total ethanol demand is boosted by 223.21%. The consumption of diesel and other petroleum products is 9.87% shorter than No Policy because of the mandate mixture with biodiesel. The Diesel B7 price is set at R\$ 2.51 per koe, which represents an increment of 117.79%. Since there is more crop used for fuel purposes, the domestic and international sugar prices rise by 113.31% and soybean prices grow 78.07%. Because of the increased demand for raw materials by the fuel mills, sugarcane and soybean production are 52.17% and 18.72 % bigger, respectively.

The results of *Status Quo*+Cap* present smaller fuel prices than *Status Quo** because of the government subsidy on oil. In *Status Quo*+Cap*, the gasohol price is R\$ 2.70 per koe, and the Diesel B7 price is R\$ 2.30 per koe, variations of -7.55% , and -8.40% if compared to *Status Quo** prices. The sugar prices drop from R\$ 915.42 per ton in *Status Quo** to R\$ 844.24 per ton in *Status Quo*+Cap*, the cap on fossil fuels cause a reduction of 1.96 Mtoe (-23.68%) in hydrous ethanol consumption due to the substitution with gasohol, while gasohol consumption is 9.70% greater. Soybean prices present opposite outcomes, rising from R\$ 1238.11 per ton to R\$ 1243.88 per ton. The rationale for this result is that the reduced price of pure petroleum diesel affects the price of blended diesel (B7) at the pump, consequently, consumers tend to use more both fuels because of the complementarity between them, expanding biodiesel demand and soybean prices. The *Status Quo*+Cap* present fuel prices more expensive than No Policy and cheaper than *Status Quo**, as can be seen in Table 25. The changes in consumer and producer surpluses between these three scenarios exhibit interesting effects on total welfare. Equating No Policy scenario to *Status Quo*+Cap*, there is a deadweight loss of 0.69% in total welfare, while *Status Quo** case generates gain on total welfare of 0.75%. This difference is mainly explained by the shrinkage of R\$ 45.46 billion in the oil industry surplus since the cap on fossil fuel prices reduces the margin in this sector when comparing scenarios (e) and (f). In Khanna et al. (2016), the cap on oil prices presented the same effects, lowering the international and domestic prices of sugar (-9.4%), gasoline price (-8.0%) and oil products prices (-10.2%) (diesel is aggregated with other petroleum products), increasing the exports of sugar in 4.2%, the gasoline consumption in 9.1% and the demand of oil products in 2.9%.

In our modeling, when the domestic demand for fuel and food are completely satisfied, the excesses of oil, sugar, and soybeans are exported. In No policy scenario, because of the lack of anhydrous and biodiesel demand, most of the Brazilian oil is used to produce oil derivatives and meet the demand of gasoline, pure diesel, and other petroleum products. As a result, the level of

oil exports is significantly small, 1.57 Mtoe. The *Status Quo** policy causes an expressive alteration on oil exports level to 26.54 Mtoe (+1,586.22%) because the national demand for fossil fuel declines expressively. Between No Policy and *Status Quo**, the sugar exports change from 30.60 to 29.43 Mtons, while soybean exports drop from 76.50 to 69.83 Mtons.

The alternative scenarios in Table 25 present important findings regarding prices. In scenario (b), the blend mandate (E27) and government taxes increase hydrous ethanol and gasohol prices to R\$ 2.63 per koe, 121.19% above the baseline level. As the consumer must use the mixture B7 in scenario (c), the Diesel B7 price is set at R\$ 2.24 per koe. Therefore, the blend mandates imply in an expansion of fuel prices for consumers, since biodiesel and ethanol present higher processing costs if compared to the production costs of oil derivatives. With taxes imposed by the government, the price of hydrous ethanol and gasoline rise 121.07%, and diesel price 59.71%. Regarding the total surplus, the largest welfare loss occurs in the scenario with taxes and E27 totaling a reduction of 3.39%, where the consumer surplus declines 39.03% for gasohol and hydrous ethanol and 12.67% for diesel and other petroleum products.

4.5.1. Carbon tax and RenovaBio policy

Table 26 shows the results of *Status Quo**, First-Best, *Status Quo**+Carbon Tax, and *Status Quo**+RenovaBio policies. The First-Best scenario is characterized by the same assumptions of No Policy in Table 25, but it includes a tax on GHG emissions of US\$ 31.20 per ton of CO₂e (R\$ 101.67). Equating First-Best to *Status Quo**, the hydrous ethanol consumption decreases 47.48% and gasoline consumption expands 70.03%. The key result concerns the government revenue of R\$ 864.53 billion, being these resources used to reduce the social damage of pollution. The First-Best policy outcomes in the highest total surplus for all scenarios evaluated, achieving approximately R\$ 2.9 trillion, there is a gain of 40.40% on welfare if compared to *Status Quo**.

The scenario *Status Quo**+Carbon Tax includes a government carbon tax on current policies of 2016, the carbon tax used on estimates ranges between US\$ 31.20 and US\$ 93.60 per ton CO₂e (R\$ 101.67 and R\$ 305.00). If applied a carbon tax of US\$ 31.20 per ton CO₂e on *Status Quo**, there is a welfare gain of 35.85% and government revenue of R\$ 848.32 billion, while if the carbon tax is US\$ 93.60 per ton CO₂e the welfare gain reaches 29.17% and the government revenue R\$ 846.13. Thus, there are decreasing returns from carbon taxation.

Table 26. Results II

Variables	Status Quo*	First-Best		Status Quo*+Carbon Tax		Status Quo*+Carbon Tax		Status Quo*+RenovaBio							
	Quo*	(R\$ 101.67/tCO ₂ e)		(R\$ 101.67/tCO ₂ e)		(R\$ 305.00/tCO ₂ e)		R\$ 0.05 per koe		R\$ 0.10 per koe		R\$ 0.25 per koe		R\$ 0.50 per koe	
	(A)	(B)	(B-A)/A	(C)	(C-A)/A	(D)	(D-A)/A	(E)	(E-A)/A	(F)	(F-A)/A	(G)	(G-A)/A	(H)	(H-A)/A
Prices															
Domestic sugar (R\$/ton)	915.42	453.66	-50.44%	939.92	2.68%	1013.43	10.71%	963.45	5.25%	1011.49	10.49%	1155.58	26.23%	1395.74	52.47%
International sugar (R\$/ton)	915.42	453.66	-50.44%	939.92	2.68%	1013.43	10.71%	963.45	5.25%	1011.49	10.49%	1155.58	26.23%	1395.74	52.47%
Domestic soybean (R\$/ton)	1238.11	716.58	-42.12%	1259.49	1.73%	1323.61	6.91%	1236.87	-0.10%	1235.63	-0.20%	1231.91	-0.50%	1225.70	-1.00%
International soybean (R\$/ton)	1238.11	716.58	-42.12%	1259.49	1.73%	1323.61	6.91%	1236.87	-0.10%	1235.63	-0.20%	1231.91	-0.50%	1225.70	-1.00%
Hydrous - producer (R\$/koe)	2.70	1.08	-59.94%	2.59	-4.07%	2.26	-16.28%	2.75	1.89%	2.80	3.77%	2.95	9.43%	3.21	18.87%
Hydrous - consumer (R\$/koe)	2.93	1.19	-59.28%	2.93	0.00%	2.93	0.00%	2.98	1.74%	3.03	3.48%	3.18	8.70%	3.43	17.41%
Gasoline - producer (R\$/koe)	1.19	0.89	-25.17%	0.89	-25.17%	-0.01	-100.67%	1.24	4.20%	1.29	8.40%	1.44	20.99%	1.69	41.98%
Gasoline - consumer (R\$/koe)	2.93	1.19	-59.28%	2.93	0.00%	2.93	0.00%	2.98	1.74%	3.03	3.48%	3.18	8.70%	3.43	17.41%
Gasohol - consumer (R\$/koe)	2.93	1.19	-59.28%	2.93	0.00%	2.93	0.00%	2.98	1.74%	3.03	3.48%	3.18	8.70%	3.43	17.41%
Diesel - producer (R\$/koe)	1.15	0.85	-25.97%	0.85	-25.97%	-0.04	-103.90%	1.20	4.33%	1.25	8.67%	1.40	21.66%	1.65	43.33%
Diesel - consumer (R\$/koe)	2.51	1.15	-54.08%	2.51	-0.12%	2.50	-0.46%	2.56	1.81%	2.60	3.61%	2.74	9.04%	2.97	18.07%
Diesel B7 - consumer (R\$/koe)	2.51	1.15	-54.08%	2.51	-0.12%	2.50	-0.46%	2.56	1.81%	2.60	3.61%	2.74	9.04%	2.97	18.07%
Other petro. prod. - producer (R\$/koe)	2.22	0.85	-61.56%	1.92	-13.62%	1.01	-54.48%	2.27	2.04%	2.31	4.09%	2.45	10.22%	2.68	20.44%
Other petro. prod. - consumer (R\$/koe)	2.51	1.15	-54.08%	2.51	-0.12%	2.50	-0.46%	2.56	1.81%	2.60	3.61%	2.74	9.04%	2.97	18.07%
Production															
Sugarcane (Mtons)	688.53	452.47	-34.28%	688.53	0.00%	688.53	0.00%	711.85	3.39%	735.16	6.77%	805.11	16.93%	921.70	33.86%
Sugar (Mtons)	40.00	41.26	3.14%	39.93	-0.17%	39.73	-0.67%	39.87	-0.33%	39.74	-0.65%	39.35	-1.63%	38.69	-3.27%
Soybean (Mtons)	116.50	97.82	-16.04%	116.19	-0.27%	115.25	-1.07%	116.46	-0.04%	116.42	-0.07%	116.29	-0.18%	116.08	-0.36%
Oil (Mtoe)	130.37	130.37	0.00%	130.37	0.00%	130.37	0.00%	130.37	0.00%	130.37	0.00%	130.37	0.00%	130.37	0.00%
Consumption															
Hydrous ethanol (Mtoe)	8.28	4.35	-47.48%	8.31	0.32%	8.39	1.29%	9.52	14.89%	10.75	29.79%	14.45	74.47%	20.62	148.95%
Anhydrous ethanol (Mtoe)	5.71	0.00	-100.00%	5.70	-0.09%	5.69	-0.37%	5.43	-4.96%	5.14	-9.92%	4.29	-24.81%	2.88	-49.61%
Total ethanol (Mtoe)	13.99	4.35	-68.91%	14.01	0.15%	14.08	0.61%	14.94	6.79%	15.89	13.59%	18.74	33.97%	23.50	67.94%
Biodiesel (Mtoe)	3.11	0.00	-100.00%	3.11	0.01%	3.11	0.06%	3.10	-0.23%	3.09	-0.46%	3.07	-1.14%	3.04	-2.29%
Gasoline (Mtoe)	22.98	39.07	70.03%	22.96	-0.09%	22.89	-0.37%	21.84	-4.96%	20.70	-9.92%	17.28	-24.81%	11.58	-49.61%
Diesel and other petro. prod. (Mtoe)	80.86	89.71	10.95%	80.87	0.01%	80.90	0.06%	80.67	-0.23%	80.49	-0.46%	79.93	-1.14%	79.01	-2.29%
Exports															
Sugar (Mtons)	29.43	30.54	3.78%	29.37	-0.20%	29.20	-0.80%	29.32	-0.39%	29.20	-0.79%	28.85	-1.96%	28.28	-3.93%
Soybean (Mtons)	69.83	76.24	9.18%	69.56	-0.38%	68.78	-1.50%	69.84	0.02%	69.86	0.04%	69.90	0.11%	69.98	0.22%
Oil (Mtoe)	26.54	1.60	-93.99%	26.55	0.04%	26.58	0.15%	27.86	4.99%	29.19	9.98%	33.16	24.96%	39.79	49.92%
Consumer surplus															
Gasohol and ethanol (B R\$)	147.42	253.41	71.90%	147.45	0.02%	147.52	0.07%	146.97	-0.30%	146.53	-0.60%	145.27	-1.46%	143.37	-2.75%
Diesel B7 and other petro. prod. (B R\$)	777.86	951.96	22.38%	778.09	0.03%	778.80	0.12%	774.18	-0.47%	770.50	-0.95%	759.54	-2.36%	741.44	-4.68%
Sugar (B R\$)	178.27	183.18	2.76%	178.01	-0.15%	177.23	-0.58%	177.76	-0.28%	177.25	-0.57%	175.74	-1.42%	173.23	-2.83%
Soybean (B R\$)	82.30	93.22	13.26%	81.87	-0.53%	80.58	-2.10%	82.33	0.03%	82.35	0.06%	82.43	0.15%	82.56	0.31%
Producer surplus															
Oil industry (B R\$)	131.59	71.16	-45.92%	131.59	0.00%	131.57	-0.02%	130.82	-0.59%	130.05	-1.17%	127.74	-2.93%	123.88	-5.86%
Sugarcane industry (B R\$)	276.14	211.17	-23.53%	275.42	-0.26%	273.26	-1.04%	284.77	3.13%	293.82	6.40%	323.43	17.13%	381.03	37.99%
Soybean industry (B R\$)	460.90	362.58	-21.33%	456.78	-0.89%	444.53	-3.55%	460.64	-0.06%	460.39	-0.11%	459.63	-0.28%	458.36	-0.55%
Government revenue (B R\$)	92.37	864.53	835.95%	848.32	818.39%	846.13	816.02%	90.81	-1.69%	89.26	-3.37%	84.58	-8.43%	76.80	-16.86%
GHG emissions damage (B R\$)	44.14	39.07	-11.49%	40.92	-7.30%	163.54	270.54%	42.53	-3.64%	41.02	-7.06%	41.16	-6.74%	41.40	-6.21%
GHG emissions (Mtons CO ₂ e)	434.14	384.27	-11.49%	402.45	-7.30%	402.16	-7.37%	418.32	-3.64%	403.48	-7.06%	404.86	-6.74%	407.17	-6.21%
Total surplus (B R\$)	2102.70	2952.15	40.40%	2856.60	35.85%	2716.08	29.17%	2105.75	0.14%	2109.13	0.31%	2117.19	0.69%	2139.26	1.74%

Source: prepared by the authors with GAMS version 25.1.3. Note: deviations are evaluated relative to *Status Quo**, column (A); *Status Quo** policy includes government fuel taxes and blend mandates.

As the price of CBIO in the RenovaBio policy is uncertain due to the lack of consolidation of the carbon credit market proposed by the Brazilian government until the moment, we evaluate several scenarios and compare them to *Status Quo**. The price of CBIO is exogenous, ranging from R\$ 0.05 to R\$ 0.50 per koe for all fuels included in the modeling. Table 26 shows the results of this new policy. When CBIO is R\$ 0.05 per koe, the domestic and international sugar price rise 5.25%, but if CBIO price is equal to R\$ 0.50 per koe, these prices increase 52.47%, which is attributed to the expansion of hydrous ethanol consumption changing from 14.89% to 148.95%, and the variation of pure gasoline and anhydrous ethanol consumption between -4.96% and -49.61% . Therefore, consumers tend to substitute gasohol with hydrous ethanol. The soybean prices are lowered as the price of CBIO increases, the difference ranges from -0.10% to -1.00% . This occurs because of the growth of pure diesel price by 1.81%-18.07%, affecting the consumption of pure diesel in -0.23% up to -2.29% , lessening the soybean need for biodiesel production, and expanding the availability of soybeans for food production and exports. With RenovaBio policy, due to the blend mandates, the complementarity of pure diesel and biodiesel results in less biodiesel production, as well as the obligatory mix of anhydrous and pure gasoline causes lower anhydrous production. Figure 15 shows the share of consumption of each type of fuel under the RenovaBio policy.

Figure 15. Share of fuel consumption with RenovaBio policy

Source: prepared by the authors.

Without CBIOs, the share of hydrous ethanol is 6.85% of the total fuel consumption. But if the CBIO price is R\$ 0.50 per koe, it achieves 17.61%, the gasoline's share reduces 9.11 percentage points (p.p.), and the share of anhydrous ethanol declines 2.26 p.p. (Figure 15). The hydrous ethanol industry is boosted because of the existence of flex-fuel vehicles in Brazil, and

the level of consumption of biofuel significantly rises since there is gasohol substitution to hydrous ethanol.

RenovaBio policy means the transfer of revenues from fossil fuel producers to the biofuel industry, that is, one additional cost for gasoline, diesel, and other petroleum products sectors and extra revenue for ethanol and biodiesel mills. But, if fossil fuel producers can allocate the cost of CBIOs to consumers, thus, there is a variation on surpluses and total welfare, as can be seen in Table 26. The consumer surplus of gasohol and hydrous ethanol is lowered by 0.30%-2.75%, from R\$ 146.97 to R\$ 143.37 billion. As the consumption of pure diesel drops, it affects negatively the consumer surplus of diesel B7 and other petroleum products, from -0.47% to -4.68%, resulting in a loss of R\$ 3.68 billion up to R\$ 36.42 billion if compared to *Status Quo**. The sugar consumer surplus falls because mills begin to produce more hydrous ethanol. Soybean consumer surplus rises due to the smaller amount of biodiesel production. The surplus of sugarcane industry is boosted, this sector remains 37.99% better off (R\$ 104.90 billion), and soybean industry is worse off, with a loss of 0.55% (+R\$ 2.54 billion) if CBIO price equals to R\$ 0.50. Moreover, because of fossil fuel consumption reductions, the government revenue is lowered by 1.69%-16.86%, a loss between R\$ 1.56 and R\$ 15.57 billion considering our interval of CBIO prices.

The RenovaBio policy aims the reduction of GHG emissions from fossil fuel and the expansion of biofuel production and consumption. As demonstrated in Figure 15, the share of biofuel consumption grows due to the hydrous ethanol demand. Furthermore, the level of GHG emissions decreases from 434.14 Mtons CO₂e when CBIO is zero to 418.32 Mtons CO₂e if CBIO is R\$ 0.05 per koe, a reduction of 3.64% (Figure 16).

Figure 16. Variation of CO₂e emissions and total surplus with RenovaBio policy for different prices of carbon credits (CBIOs)

Source: prepared by the authors.

Our results point to 403.48 Mtons CO₂e as the minimum level of GHG emissions when CBIO price is R\$0.10 per koe, meaning -7.06% of GHG emissions if compared to *Status Quo**. Finally, the total welfare tends to increase as the price of CBIO upsurges, this effect is due to the gains on biofuel producer surplus (Figure 16).

From our findings, we observe that the First-Best scenario presents a lower level of CO₂e emissions, but the assumptions concerning this policy are strong, tending to deteriorate the anhydrous ethanol sector and benefit the consumption of fossil fuels. The *Status Quo**+Carbon Tax policy is adequate because it reduces the level of GHG emissions, but it does not contribute to the strengthening of the biofuel industry in Brazil. The RenovaBio policy is a more realistic scenario because it considers the Brazilian legislation, contributes to abate CO₂e emissions, improving the biofuel industry, and reducing the dependence on fossil fuels. Moreover, three factors can boost the abatement of GHG emissions and the gains on social welfare in RenovaBio policy: A) to improve the energy efficiency, mainly in the ethanol sector, meaning more energy content per liter of ethanol; B) to reduce the level of emissions from soybean cultivation and biodiesel production, that is, initiatives to foster the Research and Development aiming to decrease the CO₂e emissions on life cycle; and C) to expand biofuel blend mandates, especially the biodiesel mixture in petroleum diesel.

4.5.2. Sensitivity analysis

The chosen elasticities play an important role in modeling. The welfare effects of policy scenarios depend on assumptions concerning supply and demand. Thus, we carry out a sensitivity analysis assuming elasticities uniformly distributed within the intervals presented in Table F1 (Appendix F). We run 50 times the *Status Quo**+RenovaBio policy including carbon credits (CBIOs) of R\$ 0.10 per koe and using random combinations of elasticities without replacement, since this level of CBIO price results in the maximum reduction of GHG emissions. These outcomes are called *Status Quo^R*. We calculate the percentage deviations between *Status Quo^R* and *Status Quo** (displayed in Table 26) because the last one minimizes errors to current values of 2016 and assumes specific elasticities from economic literature. The results of sensitivity analysis are displayed as boxplots in Figures 17, 18, and 19. The top line of the boxplot shows the maximum positive deviation, the bottom line indicates the lowest change, and the central line is the median. The boxes in the graphs represent the interquartile range, being the bottom of the box the 25th percentile, and the top the 75th percentile. The dot represents the average deviation between *Status Quo** and *Status Quo^R*, and the triangle is the effect measured between *Status Quo**

and model (F) in Table 26 (*Status Quo**+RenovaBio), which we call *Status Quo*^{R*} in this section because it uses selected elasticities to minimize errors.

The consumer surpluses can suffer huge deviations depending on elasticities. In Figure 17a, the average loss on gasohol and ethanol consumer surplus achieves 55.67% in *Status Quo*^R simulations, while comparing *Status Quo** to *Status Quo*^{R*} the loss is 0.60% (the triangle in Figure 17a). For diesel B7 and other petroleum products, the average loss on simulations is 61.51% against -0.95% from *Status Quo*^{R*}. Regarding the food sector, on average in *Status Quo*^R, the consumer surplus in sugar market decreases 86.45%, and soybean consumers tend to gain 147.10%. Equating *Status Quo** to *Status Quo*^{R*}, these effects are -0.57% and 0.06%, respectively.

Figure 17. Boxplot for consumer surplus

Source: prepared by the authors with software RStudio 1.2.1578 and GAMS 25.1.3.

Note: the triangle represents values from *Status Quo**+RenovaBio policy with the price of carbon credit equals to R\$ 0.10 per koe (model F, Table 26); the dot represents the average difference between the current scenario of 2016 (*Status Quo**) and the simulations (*Status Quo*^{R*}).

The producer surpluses change expressively with random elasticities. For the oil industry, the highest loss is 1.15%, close to *Status Quo*^{R*} estimative of -1.17% (the triangle in Figure 18a). For the sugarcane industry is expected a maximum surplus gain of 12.25%. The soybeans industry can present an average loss of 21.30%, contrasting with -0.11% obtained in *Status Quo*^{R*}. Figure 19 presents the results on government revenue, CO₂e emissions, and total welfare.

Figure 18. Boxplot for producer surplus

Source: prepared by the authors with software RStudio 1.2.1578 and GAMS 25.1.3.

Note: the triangle represents values from *Status Quo**+RenovaBio policy with the price of carbon credit equals to R\$ 0.10 per koe (model F, Table 26); the dot represents the average difference between the current scenario of 2016 (*Status Quo**) and the simulations (*Status Quo*^{R*}).

Figure 19. Boxplot for government revenue, CO₂e emissions, and total surplus

Source: prepared by the authors with software RStudio 1.2.1578 and GAMS 25.1.3.

Note: the triangle represents values from *Status Quo**+RenovaBio policy with the price of carbon credit equals to R\$ 0.10 per koe (model F, Table 26); the dot represents the average difference between the current scenario of 2016 (*Status Quo**) and the simulations (*Status Quo*^{R*}).

In RenovaBio policy, the government revenue does not change, since there is no extra tax going to pollution abatement. The variations observed in the boxplot reflect differences due to elasticities, customer preferences, and fuel substitution because the costs of CBIOs are passed on to consumers. The average difference obtained in simulated scenarios is -2.04% , and under *Status Quo*^{R*} policy is -3.37% , as presented by the triangle in Figure 19a.

The RenovaBio policy is a good opportunity to abate the level of GHG emissions. Figure 19b reveals that the average variation on CO₂e emissions under the RenovaBio policy is -3.93% , and the maximum effect is -7.20% of CO₂e emissions from consumption and production of fuel and food. Our estimate from *Status Quo*^{R*} model indicates -7.06% , which is close to the 25th percentile of -7.03% from data simulation in the boxplot. It is important to highlight that the reduction on GHG emissions from RenovaBio policy can decrease the welfare, the sensitivity analysis point to an average deadweight loss of 37.12% in the total surplus, but estimates considering elasticities that minimizes the errors (*Status Quo*^{R*}) indicate a gain of 0.31% , totaling R\$ 6.43 billion.

4.6. Conclusion

In Brazil, the diverse existing laws concerning fuel markets create a complex market structure. The National Biodiesel Production and Use Program (PNPB) from 2004, the new pricing system of fossil fuels adopted by Petrobras in 2017, and the proposal of National Biofuel Policy (RenovaBio) are policies that combine different objectives for fuel consumption and production in the country. The PNPB established the blend mandate of biodiesel in petroleum diesel, promoting agribusiness and family farming, while RenovaBio tends to mitigate greenhouse gas emissions through the establishment of a market of carbon credits, where fossil fuel producers must buy the carbon credits issued by the biofuel industry.

The blend mandates of anhydrous ethanol in gasoline and biodiesel in petroleum diesel are mechanisms that present effects on food markets, since ethanol and sugar are obtained from sugarcane, and biodiesel is produced mainly from soybeans in Brazil. This paper related fuel and food markets in Brazil using a partial equilibrium model able to measure the disaggregated and combined effects of fuel policies on prices, consumption, and production of gasohol, hydrous ethanol, blended diesel, other petroleum products, soybeans, and sugar. Through several scenarios and sensitivity analyses, we evaluate the impacts on consumer and producer surpluses, as well as on government revenue and greenhouse gas emissions level. The data refer to the year 2016, and the elasticities were obtained from the economic literature. The *Status Quo*^{*} scenario assumes current policies of 2016, showing that the model presented a good calibration because

the main outcomes exhibited errors less than 10% if compared to values from the Brazilian economy. The First-Best scenario accounts for a competitive market structure with a carbon tax on GHG emissions imposed by the government to reduce pollution damages. This policy presents the maximum level of surplus, resulting in 40.40% of welfare gain and -11.49% on GHG emissions if equated to *Status Quo**. The *Status Quo**+RenovaBio policy combines current fuel policies, an extra cost of carbon credits for fossil fuel suppliers, and additional revenue from carbon credits for biofuel producers. In *Status Quo**+RenovaBio with a carbon credit price of R\$ 0.10 per koe, there is an abatement of 7.06% on GHG emissions, and expansion on total welfare of 0.31%, resulting in a gain of R\$ 6.43 billion in the Brazilian economy. Due to the substitution between hydrous ethanol and gasohol (anhydrous ethanol blended with pure gasoline), the RenovaBio policy tends to expand the hydrous ethanol share regarding total fuel consumption, while the share of gasohol decreases. The share of diesel and other petroleum products remains stable, as well as biodiesel share since diesel and biodiesel are complementary because of the obligatory mixture. Therefore, considering our scenarios, the RenovaBio is an adequate policy in reducing GHG emissions, promoting the biofuel industry and consumption, and decreasing the dependence on fossil fuels. Furthermore, this policy is efficient because it increases the level of total welfare in the economy.

Brazil is an emerging economy. Thus, actions to promote the low dependence on fossil fuels and reduce the level of pollution mean a safe path for development. The blend mandates in Brazil are important policies to reduce GHG emissions and boost agricultural sectors. The RenovaBio policy is an excellent opportunity to mitigate the pollution effects through market mechanisms. The government, private companies, and research agencies are key players to improve RenovaBio policy outcomes, contributing to advance the energy efficiency of supplied biofuels; reduce emissions of GHG from soybean and sugarcane cultivation and processing; and, determining the viability of expansion of the mandatory mixture between biofuels and fossil fuels.

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4.8. Appendix E: mathematical model

I - Mathematical model for *Status Quo*+RenovaBio policy

The first-order conditions of (50) are:

$$\frac{\partial L_1}{\partial g} = \alpha_{ge} + \beta_{ge}(g + \varphi_g h + \varphi_g a) + t^o \gamma_g - \alpha_o \gamma_g \quad (E1)$$

$$\begin{aligned} & - \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_g - z_g - t^g - p^{cbio} + \frac{(1 - \theta) \lambda_g}{\theta} \\ & = 0 \end{aligned}$$

$$\frac{\partial L_1}{\partial k} = \alpha_{kb} + \beta_{kb}(k + b \varphi_k + op \varphi_{op}) + t^o \gamma_k - \alpha_o \gamma_k \quad (E2)$$

$$\begin{aligned} & - \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_k - z_k - t^k - p^{cbio} + \frac{(1 - \phi) \lambda_k}{\phi} \\ & = 0 \end{aligned}$$

$$\frac{\partial L_1}{\partial op} = \alpha_{kb} \varphi_{op} + \beta_{kb} \varphi_{op}(k + \varphi_k b + \varphi_{op} op) + \alpha_{op} + \beta_{op} op + t^o \gamma_{op} \quad (E3)$$

$$\begin{aligned} & - \alpha_o \gamma_{op} - \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_{op} - z_{op} - t^{op} - p^{cbio} \\ & = 0 \end{aligned}$$

$$\frac{\partial L_1}{\partial h} = \alpha_{ge} \varphi_g + \beta_{ge} \varphi_g(g + \varphi_g h + \varphi_g a) - \alpha_{sc} \tau_h \quad (E4)$$

$$- \beta_{sc}(\tau_a a + \tau_h h + \tau_s(s^n + s^x)) \tau_h - z_h - t^h + p^{cbio} = 0$$

$$\frac{\partial L_1}{\partial a} = \alpha_{ge} \varphi_g + \beta_{ge} \varphi_g(g + \varphi_g h + \varphi_g a) - \alpha_{sc} \tau_a \quad (E5)$$

$$- \beta_{sc}(\tau_a a + \tau_h h + \tau_s(s^n + s^x)) \tau_a - z_a - t^a + p^{cbio} - \lambda_g = 0$$

$$\frac{\partial L_1}{\partial b} = \alpha_{kb} \varphi_k + \beta_{kb} \varphi_k(k + b \varphi_k + op \varphi_{op}) - \alpha_{sb} \tau_{sb} - \beta_{sb}(\tau_{sb} b + sb^n + sb^x) \tau_{sb} \quad (E6)$$

$$- z_b - t^b + p^{cbio} - \lambda_k = 0$$

$$\frac{\partial L_1}{\partial s^n} = \alpha_{s^n} + \beta_{s^n} s^n - \alpha_{sc} \tau_s - \beta_{sc} \tau_s(\tau_a a + \tau_h h + \tau_s(s^n + s^x)) - z_s = 0 \quad (E7)$$

$$\frac{\partial L_1}{\partial s^x} = \alpha_{s^x} + \beta_{s^x} s^x - \alpha_{sc} \tau_s - \beta_{sc} \tau_s(\tau_a a + \tau_h h + \tau_s(s^n + s^x)) - z_s = 0 \quad (E8)$$

$$\frac{\partial L_1}{\partial sb^n} = \alpha_{sb^n} + \beta_{sb^n} sb^n - \alpha_{sb} - \beta_{sb}(\tau_{sb} b + sb^n + sb^x) - z_{sb} = 0 \quad (E9)$$

$$\frac{\partial L_1}{\partial sb^x} = \alpha_{sb^x} + \beta_{sb^x} sb^x - \alpha_{sb} - \beta_{sb}(\tau_{sb} b + sb^n + sb^x) - z_{sb} = 0 \quad (E10)$$

$$\frac{\partial L_1}{\partial o^x} = p_o^w - \alpha_o - \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) = 0 \quad (E11)$$

From the equation (E11), the domestic oil price is given by the international oil price (E12). Consequently, the level of production is given by exogenous factors.

$$p_o^w = \alpha_o + \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \quad (E12)$$

The price of *ge* (P_{ge}), gasohol (or gasoline C), is the weighted average of pure gasoline (gasoline A) and anhydrous ethanol:

$$P^{ge} g + P^{ge} \varphi_g a \quad (E13)$$

From equations (E1), (E5), and (E12), it is possible to find the average price P^{ge} . The blend mandate is modeled as an *ad valorem* subsidy on ethanol consumption, λ_g , and an *ad valorem* tax on gasoline consumption $(1 - \theta)\lambda_g/\theta$. The first share of (E13) is given by (E14), which is formed by the international oil price, oil cap, production costs of gasoline A, taxes applied by the government, CBIO price, and the *ad valorem* tax from the blend mandate $(1 - \theta)\lambda_g/\theta$. Equation (E14) can be rewritten as (E15):

$$[\alpha_{ge} + \beta_{ge}(g + \varphi_g h + \varphi_g a)]g \quad (E14)$$

$$= \left[-t^o \gamma_g + \alpha_o \gamma_g + \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_g + z_g + t^g \right. \\ \left. + p^{cbio} - \frac{(1 - \theta)\lambda_g}{\theta} \right] g$$

$$P^{ge} g = \left[(p_o^w - t^o) \gamma_g + z_g + t^g + p^{cbio} - \frac{(1 - \theta)\lambda_g}{\theta} \right] g \quad (E15)$$

If the marginal cost of sugarcane is (E16). The second share of (E13) is (E17), which can be reduced to (E18), that is, the marginal cost of sugarcane, the cost of ethanol production, and taxes imposed by the government, discounting CBIO price and the implicit subsidy (λ_g). Finally, P^{ge} is expressed as (E19) and rewritten as (E20):

$$P^{sc} = \alpha_{sc} + \beta_{sc}(\tau_a a + \tau_h h + \tau_s(s^n + s^x)) \quad (E16)$$

$$[\alpha_{ge}\varphi_g + \beta_{ge}\varphi_g(g + \varphi_g h + \varphi_g a)]a \quad (E17)$$

$$= [\alpha_{sc}\tau_a + \beta_{sc}(\tau_a a + \tau_h h + \tau_s(s^n + s^x))\tau_a + z_a + t^a - p^{cbio} + \lambda_g]a$$

$$P^{ge}\varphi_g a = [P^{sc}\tau_a + z_a + t^a - p^{cbio} + \lambda_g]a \quad (E18)$$

$$P^{ge}g + P^{ge}\varphi_g a = \left[(p_o^w - t^o)\gamma_g + z_g + t^g + p^{cbio} - \frac{(1-\theta)\lambda_g}{\theta} \right]g \quad (E19)$$

$$+ [P^{sc}\tau_a + z_a + t^a - p^{cbio} + \lambda_g]a$$

$$P^{ge} = \frac{\left[(p_o^w - t^o)\gamma_g + z_g + t^g + p^{cbio} - \frac{(1-\theta)\lambda_g}{\theta} \right]g + [P^{sc}\tau_a + z_a + t^a - p^{cbio} + \lambda_g]a}{g + \varphi_g a} \quad (E20)$$

The price of hydrous ethanol (P^h) is composed of the international price of oil, the cost and taxes of gasoline A, and the *ad valorem* tax due to the blend mandate. Furthermore, it depends on sugarcane price, costs and taxes of hydrous ethanol, CBIO price, and the *ad valorem* subsidy (λ_g). To observe this price, we take the energy equivalent rate of blended fuel in terms of gasoline (E21), which is equal to (E22), and the energy content of blended fuel (E23). P^h is defined as (E24), which is rewritten as (E25).

$$P^h = \varphi_g P^{ge} \quad (E21)$$

$$P^h = \varphi_g [\alpha_{ge} + \beta_{ge}(g + \varphi_g h + \varphi_g a)] \quad (E22)$$

$$(1 - \theta) + \theta\varphi_g \quad (E23)$$

$$P^h(1 - \theta) + P^h\theta\varphi_g = \quad (E24)$$

$$\varphi_g \left\{ \left[(p_o^w - t^o)\gamma_g + z_g + t^g + p^{cbio} - \frac{(1-\theta)\lambda_g}{\theta} \right] (1 - \theta) + [P^{sc}\tau_a + z_a + t^a - p^{cbio} + \lambda_g]\theta \right\} \\ P^h = \frac{\varphi_g \left\{ \left[(p_o^w - t^o)\gamma_g + z_g + t^g + p^{cbio} - \frac{(1-\theta)\lambda_g}{\theta} \right] (1 - \theta) + [P^{sc}\tau_a + z_a + t^a - p^{cbio} + \lambda_g]\theta \right\}}{(1 - \theta) + \theta\varphi_g} \quad (E25)$$

The marginal cost of soybeans is:

$$P^{sb} = \alpha_{sb} + \beta_{sb}(\tau_{sb}b + sb^n + sb^x) \quad (E26)$$

The price of petroleum diesel blended with biodiesel (P^{kb}) is the weighted average of pure diesel and biodiesel (E27). From equations (E2), (E6), and (E27), we obtain (E28), (E29), (E30),

(E31), and (E32), being rewritten as (E33). From (E32) and (E33), we can see that the first share of P^{kb} is formed by international oil price, the cap on oil price, the costs of production of pure diesel, the government taxes, the price of CBIO, and the blend mandate of biodiesel in pure diesel, accounted as $(1 - \phi)\lambda_k/\phi$. The second share of P^{kb} is determined by the soybean price, the processing cost of biodiesel, taxes imposed by the government, the price of CBIO, and λ_k , the implicit subsidy.

$$P^{kb}k + P^{kb}\varphi_kb \quad (E27)$$

$$[\alpha_{kb} + \beta_{kb}(k + b\varphi_k + op\varphi_{op})]k \quad (E28)$$

$$= \left[-t^o\gamma_k + \alpha_o\gamma_k + \beta_o(\gamma_g g + \gamma_k k + \gamma_{op}op + o^x)\gamma_k + z_k + t^k + p^{cbio} - \frac{(1 - \phi)\lambda_k}{\phi} \right] k$$

$$P^{kb}k = \left[(p_o^w - t^o)\gamma_k + z_k + t^k + p^{cbio} - \frac{(1 - \phi)\lambda_k}{\phi} \right] k \quad (E29)$$

$$[\alpha_{kb}\varphi_k + \beta_{kb}\varphi_k(k + b\varphi_k + op\varphi_{op})]b \quad (E30)$$

$$= [\alpha_{sb}\tau_{sb} + \beta_{sb}\tau_{sb}(\tau_{sb}b + sb^n + sb^x) + z_b + t^b - p^{cbio} + \lambda_k]b$$

$$P^{kb}\varphi_kb = [P^{sb}\tau_{sb} + z_b + t^b - p^{cbio} + \lambda_k]b \quad (E31)$$

$$P^{kb}k + P^{kb}\varphi_kb \quad (E32)$$

$$= \left[(p_o^w - t^o) + z_k + t^k + p^{cbio} - \frac{(1 - \phi)\lambda_k}{\phi} \right] k$$

$$+ [P^{sb}\tau_{sb} + z_b + t^b - p^{cbio} + \lambda_k]b$$

$$P^{kb} = \frac{\left[(p_o^w - t^o) + z_k + t^k + p^{cbio} - \frac{(1 - \phi)\lambda_k}{\phi} \right] k + [P^{sb}\tau_{sb} + z_b + t^b - p^{cbio} + \lambda_k]b}{k + \varphi_kb} \quad (E33)$$

It is important to highlight that the sugar price, as well as the hydrous ethanol price, depends on the international oil price, there is a relationship between these two variables due to the marginal benefits of producing sugar and ethanol jointly. Using equation (E7), we obtain the domestic sugar price (E34) or (E35). Solving equations (E4) and (E7) for the marginal cost of sugarcane (E16), we have (E36) and (E37).

$$P^{s^n} = \alpha_{s^n} + \beta_{s^n}s^n \quad (E34)$$

$$P^{s^n} = \alpha_{sc}\tau_s + \beta_{sc}\tau_s(\tau_a a + \tau_h h + \tau_s(s^n + s^x)) + z_s \quad (E35)$$

$$P^{s^n} = P^{sc}\tau_s + z_s \quad (E36)$$

$$P^{sc} = \frac{P^{s^n} - z_s}{\tau_s} \quad (E37)$$

From equations (E4) and (E37):

$$\alpha_{ge}\varphi_g + \beta_{ge}\varphi_g(g + \varphi_g h + \varphi_g a) \quad (E38)$$

$$= \alpha_{sc}\tau_h + \beta_{sc}(\tau_a a + \tau_h h + \tau_s(s^n + s^x))\tau_h + z_h + t^h - p^{cbio}$$

$$\varphi_g P^{ge} = P^{sc}\tau_h + z_h + t^h - p^{cbio} \quad (E39)$$

$$\varphi_g P^{ge} = (P^{s^n} - z_s)\frac{\tau_h}{\tau_s} + z_h + t^h - p^{cbio} \quad (E40)$$

Therefore, according to equations (E20), (E25), and (E40), if the price of blended gasoline (gasoline C) increases due to a rise in the international oil price, the price of sugar will augment too. From equation (E9), we obtain the domestic price of soybeans (E41) or (E42). Solving equations (E6) and (E9) for the marginal cost of soybeans (E42), we have (E44):

$$P^{sb^n} = \alpha_{sb^n} + \beta_{sb^n}sb^n \quad (E41)$$

$$P^{sb^n} = \alpha_{sb} + \beta_{sb}(\tau_{sb}b + sb^n + sb^x) + z_{sb} \quad (E42)$$

$$P^{sb^n} = P^{sb} + z_{sb} \quad (E43)$$

$$P^{sb} = P^{sb^n} - z_{sb} \quad (E44)$$

From equations (E6) and (E44), we get (E45) and (E46). Equation (E46) can be rewritten as (E47), which determines that if the international oil price increases, the price of blended diesel goes up, affecting the soybean prices.

$$\alpha_{kb}\varphi_k + \beta_{kb}\varphi_k(k + b\varphi_k + op\varphi_{op}) \quad (E45)$$

$$= \alpha_{sb}\tau_{sb} - \beta_{sb}\tau_{sb}(\tau_{sb}b + sb^n + sb^x) + z_b + t^b - p^{cbio} + \lambda_k$$

$$\varphi_k P^{kb} = P^{sb}\tau_{sb} + z_b + t^b - p^{cbio} + \lambda_k \quad (E46)$$

$$\varphi_k P^{kb} = (P^{sb^n} - z_{sb})\tau_{sb} + z_b + t^b - p^{cbio} + \lambda_k \quad (E47)$$

The price of other petroleum (P^{op}) products is given by:

$$\varphi_{op}P^{op} = \alpha_{kb}\varphi_{op} + \beta_{kb}\varphi_{op}(k + \varphi_k b + \varphi_{op}op) \quad (\text{E48})$$

$$\varphi_{op}P^{op} = \alpha_o\gamma_{op} + \beta_o(\gamma_g g + \gamma_k k + \gamma_{op}op + o^x)\gamma_{op} + z_{op} + t^{op} + p^{cbio} \quad (\text{E49})$$

$$\varphi_{op}P^{op} = p_o^w\gamma_{op} + z_{op} + t^{op} + p^{cbio} \quad (\text{E50})$$

II - Mathematical model for the First-Best policy

The first-order conditions of (51) are:

$$\frac{\partial L_2}{\partial g} = \alpha_{ge} + \beta_{ge}(g + \varphi_g h + \varphi_g a) - \alpha_o \gamma_g - \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_g \quad (E51)$$

$$- z_g - \varepsilon^m \sigma_o \gamma_g = 0$$

$$\frac{\partial L_2}{\partial k} = \alpha_{kb} + \beta_{kb}(k + b \varphi_k + op \varphi_{op}) - \alpha_o \gamma_k - \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_k \quad (E52)$$

$$- z_k - \varepsilon^m \sigma_o \gamma_k = 0$$

$$\frac{\partial L_2}{\partial op} = \alpha_{kb} \varphi_{op} + \beta_{kb} \varphi_{op}(k + \varphi_k b + \varphi_{op} op) \quad (E53)$$

$$- \alpha_o \gamma_{op} - \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_{op} - z_{op} - \varepsilon^m \sigma_o \gamma_{op} = 0$$

$$\frac{\partial L_2}{\partial h} = \alpha_{ge} \varphi_g + \beta_{ge} \varphi_g(g + \varphi_g h + \varphi_g a) - \alpha_{sc} \tau_h - \beta_{sc}(\tau_h h + \tau_s(s^n + s^x)) \tau_h \quad (E54)$$

$$- z_h - \varepsilon^m \sigma_h = 0$$

$$\frac{\partial L_2}{\partial s^n} = \alpha_{s^n} + \beta_{s^n} s^n - \alpha_{sc} \tau_s - \beta_{sc} \tau_s(\tau_a a + \tau_h h + \tau_s(s^n + s^x)) - z_s - \varepsilon^m \sigma_s = 0 \quad (E55)$$

$$\frac{\partial L_2}{\partial s^x} = \alpha_{s^x} + \beta_{s^x} s^x - \alpha_{sc} \tau_s - \beta_{sc} \tau_s(\tau_a a + \tau_h h + \tau_s(s^n + s^x)) - z_s - \varepsilon^m \sigma_s = 0 \quad (E56)$$

$$\frac{\partial L_2}{\partial sb^n} = \alpha_{sb^n} + \beta_{sb^n} sb^n - \alpha_{sb} - \beta_{sb}(\tau_{sb} b + sb^n + sb^x) - z_{sb} - \varepsilon^m \sigma_{sb} = 0 \quad (E57)$$

$$\frac{\partial L_2}{\partial sb^x} = \alpha_{sb^x} + \beta_{sb^x} sb^x - \alpha_{sb} - \beta_{sb}(\tau_{sb} b + sb^n + sb^x) - z_{sb} - \varepsilon^m \sigma_{sb} = 0 \quad (E58)$$

$$\frac{\partial L_2}{\partial o^x} = \bar{p}_o^w - \alpha_o - \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) - \varepsilon^m \sigma_o = 0 \quad (E59)$$

From equation (E59), the price of oil is defined as (E60). It will be higher than the international level due to the carbon tax applied by the government ($\varepsilon^m \sigma_o$), as a consequence, oil consumption will be reduced.

$$\bar{p}_o^w = \alpha_o + \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) + \varepsilon^m \sigma_o \quad (E60)$$

From (E51), the price of ge (pure gasoline, since there is no blend with anhydrous ethanol) is given by the international price of oil, accounting the carbon tax given the level of emissions $\varepsilon^m \sigma_o \gamma_g$, and the cost of gasoline production (z_g), as can be seen in (E62).

$$\alpha_{ge} + \beta_{ge}(g + \varphi_g h + \varphi_g a) \quad (\text{E61})$$

$$= \alpha_o \gamma_g + \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_g + z_g + \varepsilon^m \sigma_o \gamma_g$$

$$P^{ge} = \gamma_g \overline{p_o^w} + z_g \quad (\text{E62})$$

From (E52), we find similar results for pure diesel price (kb), as shown in (E64).

$$\alpha_{kb} + \beta_{kb}(k + b\varphi_k + op\varphi_{op}) \quad (\text{E63})$$

$$= \alpha_o \gamma_k + \beta_o(\gamma_g g + \gamma_k k + \gamma_{op} op + o^x) \gamma_k + z_k + \varepsilon^m \sigma_o \gamma_k$$

$$P^{kb} = \gamma_k \overline{p_o^w} + z_k \quad (\text{E64})$$

From (E54), the ethanol will be taxed according to the emission intensity, $\varepsilon^m \sigma_h$, as represented by (E65) and (E66).

$$\alpha_{ge} \varphi_g + \beta_{ge} \varphi_g (g + \varphi_g h + \varphi_g a) \quad (\text{E65})$$

$$= \alpha_{sc} \tau_h + \beta_{sc}(\tau_h h + \tau_s(s^n + s^x)) \tau_h + z_h + \varepsilon^m \sigma_h$$

$$\varphi_g P^{ge} = P^{sc} \tau_h + z_h + \varepsilon^m \sigma_h \quad (\text{E66})$$

Using (E55), we get (E67), (E70), and (E71). Including (E69) in (E66), we have (E71), which shows that there is a relationship between sugar price and the international oil price.

$$\alpha_{s^n} + \beta_{s^n} s^n = \alpha_{sc} \tau_s + \beta_{sc} \tau_s (\tau_a a + \tau_h h + \tau_s(s^n + s^x)) + z_s + \varepsilon^m \sigma_s \quad (\text{E67})$$

$$P^{s^n} = P^{sc} \tau_s + z_s + \varepsilon^m \sigma_s \quad (\text{E68})$$

$$P^{sc} = \frac{P^{s^n} - z_s - \varepsilon^m \sigma_s}{\tau_s} \quad (\text{E69})$$

$$\varphi_g P^{ge} = (P^{s^n} - z_s - \varepsilon^m \sigma_s) \frac{\tau_h}{\tau_s} + z_h + \varepsilon^m \sigma_h \quad (\text{E70})$$

$$\varphi_g P^{ge} - z_h = (P^{s^n} - z_s - \varepsilon^m \sigma_s) \frac{\tau_h}{\tau_s} + \varepsilon^m \sigma_h \quad (\text{E71})$$

4.9. Appendix F: data for model calibration

Table F1. Own-price elasticity of demand

Author/Year	Elasticity	Author/Year	Elasticity
Demand (Brazil)		Supply (Brazil)	
Gasoline		Oil	
Alves and Bueno (2003)	-0.465	Maxir (2017)	0.138
Silva, Tiryaki and Pontes (2009)	-0.945	Baumeister and Peersman (2013)	0.270*
	-1.505	Coyle et al. (2012)	0.260
	-0.775	Kilian and Murphy (2012)	0.020
	-1.288	Yoshino and Taghizadeh-Hesary (2014)	0.240
	-0.577	Greene and Leiby (2006)	0.070
	-0.316	Minimum	0.020
Vilela and Pinto Junior (2010)	-0.515	Average	0.166
	-0.208	Maximum	0.270
	-0.707		
	-0.578	Sugarcane	
Dahl (2012)	-0.260	Koizumi (2015)	0.429*
Santos (2013)	-0.428	FAPRI (2018)	0.200
	-0.318	Minimum	0.200
	-0.782	Average	0.315
Rodrigues and Bacchi (2016)	-0.126	Maximum	0.429
	-0.306		
	-0.244	Soybeans	
Rodrigues and Bacchi (2017)	-0.241*	Koizumi (2015)	0.349*
	-0.518	FAPRI (2018)	0.340
Huntington, Barrios and Arora (2019)	-0.480	Piketty and Menezes (2011)	0.288
Minimum	-1.505		0.195
Average	-0.552	Minimum	0.195
Maximum	-0.126	Average	0.293
		Maximum	0.349
Diesel			
Dahl (2012)	-0.320		
Almeida et al. (2016)	-0.933		
	-0.967		
Rodrigues and Losekann (2015)	-0.197		
Cardoso and Jesus (2018)	-0.160*		
Minimum	-0.967		
Average	-0.740		
Maximum	-0.160		
Sugar			
Koizumi (2015)	-0.029*		
FAPRI (2018)	-0.080		
Oliveira et al. (2017)	-0.270		
	-1.025		
	-0.617		
	-0.821		
Minimum	-1.025		
Average	-0.474		
Maximum	-0.029		
Soybeans			
Koizumi (2015)	-0.007		
FAPRI (2018)	-0.160*		
Minimum	-0.160		
Average	-0.083		
Maximum	-0.007		
Demand (Rest of World)		Demand (Rest of World)	
Sugar		Soybeans	
FAO (2002) - United States	-0.110*	Roberts and Schlenker (2013)	-0.236*
FAO (2002) - European Community	-0.120	Uri et al. (1994)	-1.360
FAPRI (European Union) (2018)	-0.100	Minimum	-1.360
Wunderlich and Kohler (2018)	-0.940	Average	-0.798
Minimum	-0.940	Maximum	-0.236
Average	-0.318		
Maximum	-0.100		

Source: prepared by the authors according to literature.

Note: *values used in model calibration.

Table F2. Data for model calibration

Description	Unit	Value in 2016	Source
Tax on CO ₂ e emissions	R\$ per ton CO ₂ e	110.09 – 305.00	Nordhaus (2017), World Bank (2019), and BCB (2019)
Tax on CO ₂ e emissions	R\$ per ton CO ₂ e	110.09 – 305.00	Nordhaus (2017), World Bank (2019), and BCB (2019)
Tax on gasoline	R\$ per koe	1.442	MME (2019) and ANP (2019a)
Tax on anhydrous and hydrous ethanol	R\$ per koe	0.226	CEPEA (2019) and FECOMBUSTÍVEIS (2017)
Tax on diesel A, pure diesel	R\$ per koe	0.689	MME (2019) and ANP (2019a)
Tax on other petroleum products	R\$ per koe	0.859	MME (2019) and ANP (2019a)
Tax on biodiesel	R\$ per koe	0.117	MME (2019), ANP (2019a), and FECOMBUSTÍVEIS (2017)
Anhydrous ethanol blending rate in oil equivalent		0.199	Authors' calculation based on data from EPE (2018)
Biodiesel blending rate in oil equivalent		0.037	Authors' calculation based on data from EPE (2018)
Margin on oil price	R\$ per koe	0.291	Authors' calculation based on EIA (2019) and ANP (2019a)
Cap on oil price	R\$ per koe	-0.220	Authors' calculation based on Khanna et al. (2016), EIA (2019), and ANP (2019a)
Price of Carbon Credits (CBIO)	R\$ per koe	[0.05, 0.50]	We use different exogenous values
Gasoline refinery cost	R\$ per koe	0.039	Petrobras (2018)
Conversion rate of liter of gasoline to toe		0.770	EPE (2018)
Gasoline marketing margins + freight	R\$ per koe	0.521	MME (2019) and ANP (2019a)
Gasoline price (before taxes + marketing margins + freight)	R\$ per koe	1.173	MME (2019) and ANP (2019a)
Gasoline demand	Million toe	24225.095	EPE (2018)
Anhydrous ethanol processing cost	R\$ per koe	0.223	CNA/PECEGE (2016; 2017; 2018)
Conversion rate of liter of anhydrous ethanol to toe		0.534	EPE (2018)
Anhydrous ethanol price (before taxes + marketing margins + freight)	R\$ per koe	1.002	CEPEA (2019) and FECOMBUSTÍVEIS (2017)
Anhydrous ethanol demand	Million toe	6014.936	EPE (2018)
Anhydrous yield in liters per ton of sugarcane	Liter per ton	73.400	CNA/PECEGE (2016; 2017; 2018)
Price elasticity of gasohol demand		-0.241	Table F1
Hydrous ethanol processing cost	R\$ per koe	0.206	CNA/PECEGE (2016; 2017; 2018)
Conversion rate of liter of anhydrous ethanol to toe		0.510	EPE (2018)
Hydrous ethanol marketing margins + freight	R\$ per koe	0.273	CEPEA (2019) and FECOMBUSTÍVEIS (2017)
Hydrous ethanol price (before taxes + marketing margins + freight)	R\$ per koe	0.863	CEPEA (2019) and FECOMBUSTÍVEIS (2017)

Source: prepared by the authors according to literature.

Table F2. Data for model calibration

Description	Unit	Value in 2016	Source
Hydrous ethanol yield in liters per ton of sugarcane	Liter per ton	76.500	CNA/PECEGE (2016; 2017; 2018)
Demand of hydrous ethanol	Million toe	8316.916	CNA/PECEGE (2016; 2017; 2018)
Diesel refinery cost	R\$ per koe	0.042	Petrobras (2018)
Conversion rate of liter of anhydrous ethanol to toe		0.848	EPE (2018)
Diesel marketing margins + freight	R\$ per koe	0.481	MME (2019)
Diesel price (before taxes + marketing margins + freight)	R\$ per koe	1.451	MME (2019)
Diesel demand	Million toe	44230.014	EPE (2018)
Other petroleum products refinery cost	R\$ per koe	0.042	Petrobras (2018)
Conversion rate of liter of other petroleum products to toe		0.848	EPE (2018)
Other petroleum products marketing margins + freight	R\$ per koe	1.413	MME (2019)
Other petroleum products price (before taxes + marketing margins + freight)	R\$ per koe	1.485	MME (2019)
Other petroleum products demand	Million toe	34301.321	EPE (2018)
Biodiesel processing cost	R\$ per koe	1.048	Vivian and Bornia (2014), Colombo (2016), and FGV (2019)
Conversion rate of liter of biodiesel to toe		0.792	EPE (2018)
Biodiesel marketing margin + freight	R\$ per koe	0.424	MME (2019) and ANP (2019a)
Biodiesel price (before taxes + marketing margins + freight)	R\$ per koe	1.504	MME (2019) and ANP (2019a)
Biodiesel demand	Million toe	3009.204	EPE (2018)
Biodiesel yield in liter per ton of soybeans	Liter per ton	148.600	CONAB (2019) and Colombo (2016)
Price elasticity of diesel B7 demand		-0.160	Table F1
Oil price	R\$ per koe	0.631	EIA (2019) and BCB (2019)
Conversion rate of liter of oil to toe		0.891	EPE (2018)
Price elasticity of oil supply		0.270	Table F1
Oil supply	Million toe	130373.189	EPE (2018)
Oil exports	Million toe	43812.000	EPE (2018)
Oil price (Rest of World)	R\$ per koe	0.631	EIA (2019) and BCB (2019)
Sugar processing cost	R\$ per ton	263.400	CNA/PECEGE (2016; 2017; 2018)
Sugar demand	Million tons	10.550	USDA-FAS (2019)
Sugar exports	Million tons	28.500	USDA-FAS (2019)
Sugar price	R\$ per ton	976.500	CEPEA (2019)
Sugar price (Rest of World)	R\$ per ton	1302.714	USDA-ERS (2019)
Price elasticity of sugar demand		-0.029	Table F1
Price elasticity of sugar demand (Rest of World)		-0.110	Table F1

Source: prepared by the authors according to literature.

Table F2. Data for model calibration

Description	Unit	Value in 2016	Source
Sugarcane supply	Million tons	651.500	USDA-FAS (2019)
Sugarcane producer price	R\$ per ton	69.665	CONAB (2019)
Price elasticity of sugarcane supply		0.429	Table F1
Tons of sugar per ton of sugarcane		0.121	CNA/PECEGE (2016; 2017; 2018)
Soybean demand for food	Million tons	20.146	USDA-FAS (2019)
Soybean exports for food	Million tons	68.807	USDA-FAS (2019)
Soybean price for food	R\$ per ton	1290.500	CEPEA (2019)
Soybean price for food (Rest of World)	R\$ per ton	1321.150	UNCTAD (2019)
Price elasticity of soybean demand		-0.160	Table F1
Price elasticity of soybean demand (Rest of World)		-0.236	Table F1
Soybean supply	Million tons	114.600	USDA-FAS (2019)
Soybean producer price	R\$ per ton	1181.930	CONAB (2019)
Price elasticity of soybean supply		0.349	Table F1

Source: prepared by the authors according to literature.

Table F3. Energy intensity and coefficients of GHG emissions

Variable	Unity	Value	Source
Gasoline CO ₂ intensity	g CO ₂ per mega joule	94.000	Khanna et al. (2016)
Diesel CO ₂ intensity	g CO ₂ per mega joule	94.000	Khanna et al. (2016)
Other petroleum products CO ₂ intensity	g CO ₂ per mega joule	94.000	Khanna et al. (2016)
Biodiesel CO ₂ intensity	g CO ₂ per mega joule	76.000	Coronado (2009) and Castanheira et al. (2015)
Oil CO ₂ intensity	g CO ₂ per mega joule	71.000	Khanna et al. (2016)
Ethanol CO ₂ intensity	g CO ₂ per mega joule	26.000	Khanna et al. (2016)
Gasoline energy density	mega joule per liter	34.800	Khanna et al. (2016)
Diesel energy density	mega joule per liter	38.600	Khanna et al. (2016)
Biodiesel energy density	mega joule per liter	32.364	National Renewable Energy Laboratory (2016) and Castanheira et al. (2015)
Oil energy density	mega joule per liter	37.000	Khanna et al. (2016)
Ethanol energy density	mega joule per liter	21.200	Khanna et al. (2016)
Emissions from sugarcane cultivation	kg CO _{2e} per ton	28.700	Khanna et al. (2016)
Emissions from sugarcane (feedstock & refineries)	kg CO _{2e} per ton	241.000	Khanna et al. (2016)
Emissions from soybeans cultivation	kg CO _{2e} per ton	314.000	Cerri et al. (2017)
Emissions from soybeans processing (feedstock & refineries)	kg CO _{2e} per ton	301.000	Cerri et al. (2017)

Source: prepared by the authors according to literature.

Table F4. Existing carbon pricing initiatives in 2016

Reference	Name of the initiative	Instrument type	Jurisdiction covered	US\$/tCO ₂ e (2016)	R\$/US\$ (2016)	R\$/tCO ₂ e (2016)
World Bank (2019)						
	Poland carbon tax	Carbon tax	Poland	0.07	3.26	0.24
	Mexico carbon tax	Carbon tax (lower)	Mexico	0.32	3.26	1.04
	Chongqing pilot ETS	ETS	Chongqing	1.21	3.26	3.93
	Shanghai pilot ETS	ETS	Shanghai	1.32	3.26	4.31
	Guangdong pilot ETS	ETS	Guangdong (except Shenzhen)	1.33	3.26	4.32
	Hubei pilot ETS	ETS	Hubei	2.12	3.26	6.90
	Tianjin pilot ETS	ETS	Tianjin	2.20	3.26	7.17
	Estonia carbon tax	Carbon tax	Estonia	2.23	3.26	7.28
	Mexico carbon tax	Carbon tax (upper)	Mexico	2.66	3.26	8.68
	Japan carbon tax	Carbon tax	Japan	2.82	3.26	9.19
	Norway carbon tax	Carbon tax (lower)	Norway	3.43	3.26	11.17
	Latvia carbon tax	Carbon tax	Latvia	3.91	3.26	12.73
	EU ETS	ETS	EU, Norway, Iceland, Liechtenstein	4.88	3.26	15.90
	Regional Greenhouse Gas Initiative (RGGI)	ETS	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont	5.24	3.26	17.07
	Shenzhen pilot ETS	ETS	Shenzhen	5.64	3.26	18.40
	Portugal carbon tax	Carbon tax	Portugal	7.45	3.26	24.27
	Beijing pilot ETS	ETS	Beijing	8.03	3.26	26.18
	Switzerland ETS	ETS	Switzerland	9.23	3.26	30.10
	California CaT	ETS	California	12.80	3.26	41.72
	Quebec CaT	ETS	Quebec	12.80	3.26	41.72
	New Zealand ETS	ETS	New Zealand	13.03	3.26	42.47
	Saitama ETS	ETS	Saitama	14.64	3.26	47.72
	Tokyo CaT	ETS	Tokyo	14.64	3.26	47.72
	Korea ETS	ETS	Republic of Korea	15.15	3.26	49.36
	Alberta TIER	ETS	Alberta	15.38	3.26	50.11
	Iceland carbon tax	Carbon tax	Iceland	18.66	3.26	60.81
	Slovenia carbon tax	Carbon tax	Slovenia	19.31	3.26	62.94
	Ireland carbon tax	Carbon tax	Ireland	22.33	3.26	72.77
	BC carbon tax	Carbon tax	British Columbia	23.06	3.26	75.16
	UK carbon price floor	Carbon tax	United Kingdom	23.73	3.26	77.32
	France carbon tax	Carbon tax	France	24.56	3.26	80.04
	Denmark carbon tax	Carbon tax	Denmark	25.61	3.26	83.47
	Norway carbon tax	Carbon tax (upper)	Norway	51.53	3.26	167.94
	Finland carbon tax	Carbon tax (other fossil fuels)	Finland	60.29	3.26	196.47
	Finland carbon tax	Carbon tax (liquid transport fuels)	Finland	64.75	3.26	211.02
	Switzerland carbon tax	Carbon tax	Switzerland	86.19	3.26	280.89
	Sweden carbon tax	Carbon tax	Sweden	130.50	3.26	425.30
Nordhaus (2017)				31.20	2.26	101.68

Source: World Bank (2019), BCB (2019), and Nordhaus (2017).

Note: ETS = emissions trading system.

4.10. Appendix G: figures of chapter 4

Figure G1. Planted area of soybean and sugarcane in Brazil (harvest 2016/2017)
Source: prepared by the authors with data from CONAB (2019) using software QGIS 2.18.24.

4.11. Appendix H: tables of chapter 4

Table H1. Planted area, production, and productivity of soybean and sugarcane in Brazil (harvest 2016/2017)

State	Soybean					Sugarcane				
	Planted area		Production		Productivity ton/ha	Planted area		Production		Productivity ton/ha
	Million (ha)	(%)	Million (ton)	(%)		Million (ton)	(%)	Million (ton)	(%)	
Roraima (RR)	0.03	0.09	0.09	0.08	3.00	0.00	0.00	0.00	0.00	0.00
Rondônia (RO)	0.30	0.87	0.93	0.82	3.14	0.00	0.04	0.14	0.02	39.94
Acre (AC)	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.01	29.68
Amazonas (AM)	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.26	0.04	72.76
Amapá (AP)	0.02	0.06	0.05	0.05	2.88	0.00	0.00	0.00	0.00	0.00
Pará (PA)	0.50	1.47	1.64	1.43	3.27	0.01	0.12	0.72	0.11	64.49
Tocantins (TO)	0.96	2.84	2.83	2.48	2.93	0.03	0.35	2.09	0.32	65.23
North	1.81	5.33	5.54	4.85	3.06	0.05	0.58	3.27	0.50	62.47
Maranhão (MA)	0.82	2.42	2.47	2.17	3.01	0.04	0.44	1.84	0.28	46.72
Piauí (PI)	0.69	2.05	2.05	1.80	2.95	0.02	0.17	0.76	0.12	50.10
Ceará (CE)	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.07	0.01	54.02
Rio Grande do Norte (RN)	0.00	0.00	0.00	0.00	0.00	0.05	0.53	1.97	0.30	40.80
Paraíba (PB)	0.00	0.00	0.00	0.00	0.00	0.11	1.22	4.86	0.74	44.01
Pernambuco (PE)	0.00	0.00	0.00	0.00	0.00	0.24	2.69	11.83	1.80	48.53
Alagoas (AL)	0.00	0.00	0.00	0.00	0.00	0.32	3.56	16.03	2.44	49.75
Sergipe (SE)	0.00	0.00	0.00	0.00	0.00	0.05	0.51	1.71	0.26	37.20
Bahia (BA)	1.58	4.66	5.12	4.49	3.24	0.04	0.44	2.37	0.36	59.13
Northeast	3.10	9.13	9.64	8.45	3.12	0.87	9.58	41.44	6.31	47.82
Mato Grosso (MT)	9.32	27.49	30.51	26.75	3.27	0.23	2.54	16.34	2.49	71.09
Mato Grosso do Sul (MS)	2.52	7.44	8.58	7.52	3.40	0.62	6.84	50.29	7.65	81.25
Goiás (Go)	3.28	9.67	10.82	9.48	3.30	0.96	10.64	67.63	10.29	70.25
Distrito Federal (DF)	0.07	0.21	0.24	0.21	3.45	0.00	0.00	0.00	0.00	0.00
Midwest	15.19	44.81	50.15	43.96	3.30	1.81	20.02	134.26	20.43	74.12
Minas Gerais (MG)	1.46	4.29	5.07	4.44	3.48	0.85	9.43	63.67	9.69	74.64
Espírito Santo (ES)	0.00	0.00	0.00	0.00	0.00	0.05	0.53	1.36	0.21	28.56
Rio de Janeiro (RJ)	0.00	0.00	0.00	0.00	0.00	0.03	0.29	1.01	0.15	38.00
São Paulo (SP)	0.90	2.64	3.08	2.70	3.45	4.77	52.75	369.93	56.29	77.50
Southeast	2.35	6.93	8.15	7.15	3.47	5.70	62.99	435.96	66.34	76.48
Paraná (PR)	5.25	15.48	19.59	17.17	3.73	0.62	6.83	42.22	6.42	68.35
Santa Catarina (SC)	0.64	1.89	2.29	2.01	3.58	0.00	0.00	0.00	0.00	0.00
Rio Grande do Sul (RS)	5.57	16.42	18.71	16.40	3.36	0.00	0.01	0.05	0.01	40.99
South	11.46	33.79	40.59	35.58	3.54	0.62	6.84	42.26	6.43	68.30
Brazil	33.91	100.00	114.08	100.00	3.36	9.05	100.00	657.18	100.00	72.62

Source: prepared by the authors with data from CONAB (2019).

Table H2. Brazilian biodiesel producing states (2016)

State	Biodiesel production	
	Thousand m ³	Share (%)
Acre (AC)	0.00	0.00%
Alagoas (AL)	0.00	0.00%
Amapá (AP)	0.00	0.00%
Amazonas (AM)	0.00	0.00%
Bahia (BA)	245.22	6.45%
Ceará (CE)	59.39	1.56%
Distrito Federal (DF)	0.00	0.00%
Espírito Santo (ES)	0.00	0.00%
Goiás (GO)	649.92	17.10%
Maranhão (MA)	0.00	0.00%
Mato Grosso (MT)	818.67	21.54%
Mato Grosso do Sul (MS)	178.24	4.69%
Minas Gerais (MG)	94.80	2.49%
Pará (PA)	0.00	0.00%
Paraíba (PB)	0.00	0.00%
Paraná (PR)	392.68	10.33%
Pernambuco (PE)	0.00	0.00%
Piauí (PI)	0.00	0.00%
Rio de Janeiro (RJ)	21.67	0.57%
Rio Grande do Norte (RN)	0.00	0.00%
Rio Grande do Sul (RS)	1074.76	28.27%
Rondônia (RO)	1.03	0.03%
Roraima (RR)	0.00	0.00%
Santa Catarina (SC)	89.25	2.35%
São Paulo (SP)	137.79	3.62%
Sergipe (SE)	0.00	0.00%
Tocantins (TO)	37.92	1.00%
Brazil	3801.34	100.00%

Source: prepared by the authors with data from ANP (2019a).

Table H3. Brazilian ethanol producing states (harvest 2016/2017)

State	Anhydrous ethanol		Hydrous ethanol (%)		Total ethanol	
	Thousand m ³	Share (%)	Thousand m ³	Share (%)	Thousand m ³	Share (%)
Acre (AC)	0.00	0.00%	3.67	0.02%	3.67	0.01%
Alagoas (AL)	275.62	2.38%	107.38	0.69%	382.99	1.41%
Amapá (AP)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Amazonas (AM)	0.00	0.00%	5.50	0.04%	5.50	0.02%
Bahia (BA)	55.67	0.48%	50.22	0.32%	105.90	0.39%
Ceará (CE)	0.00	0.00%	5.24	0.03%	5.24	0.02%
Distrito Federal (DF)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Espírito Santo (ES)	51.16	0.44%	8.73	0.06%	59.89	0.22%
Goiás (GO)	1312.68	11.33%	3071.77	19.61%	4384.46	16.09%
Maranhão (MA)	109.71	0.95%	17.65	0.11%	127.36	0.47%
Mato Grosso (MT)	524.40	4.52%	696.21	4.44%	1220.61	4.48%
Mato Grosso do Sul (MS)	806.81	6.96%	1901.71	12.14%	2708.52	9.94%
Minas Gerais (MG)	1193.06	10.29%	1448.29	9.25%	2641.34	9.69%
Pará (PA)	28.72	0.25%	4.49	0.03%	33.21	0.12%
Paraíba (PB)	138.75	1.20%	144.99	0.93%	283.74	1.04%
Paraná (PR)	616.34	5.32%	738.56	4.71%	1354.90	4.97%
Pernambuco (PE)	131.89	1.14%	203.17	1.30%	335.05	1.23%
Piauí (PI)	21.39	0.18%	0.22	0.00%	21.61	0.08%
Rio de Janeiro (RJ)	0.00	0.00%	81.82	0.52%	81.82	0.30%
Rio Grande do Norte (RN)	32.56	0.28%	28.61	0.18%	61.16	0.22%
Rio Grande do Sul (RS)	0.00	0.00%	2.91	0.02%	2.91	0.01%
Rondônia (RO)	0.00	0.00%	9.49	0.06%	9.49	0.03%
Roraima (RR)	0.00	0.00%	0.00	0.00%	0.00	0.00%
Santa Catarina (SC)	0.00	0.00%	0.00	0.00%	0.00	0.00%
São Paulo (SP)	6151.01	53.08%	7045.87	44.98%	13196.88	48.42%
Sergipe (SE)	22.65	0.20%	43.37	0.28%	66.02	0.24%
Tocantins (TO)	116.74	1.01%	45.45	0.29%	162.18	0.60%
Brazil	11589.14	100.00%	15665.30	100.00%	27254.44	100.00%

Source: prepared by the authors with data from UNICA (2019).

Table H4. Major exporters of soybean and sugar (2016)

Soybean			Sugar raw centrifugal		
Country	Value Billion (US\$)	Market share (%)	Country	Value Billion (US\$)	Market share (%)
United States of America	22.87	44.02	Brazil	8.28	56.77
Brazil	19.33	37.21	Australia	1.46	10.03
Argentina	3.23	6.22	Thailand	1.02	6.99
Canada	1.90	3.65	Guatemala	0.82	5.62
Paraguay	1.82	3.50	Mexico	0.39	2.70
Uruguay	0.86	1.65	Cuba	0.35	2.38
Ukraine	0.47	0.90	Eswatini	0.25	1.73
Netherlands	0.38	0.73	Argentina	0.14	0.93
Russian Federation	0.13	0.26	El Salvador	0.13	0.86
China, mainland	0.11	0.21	India	0.11	0.78
Turkey	0.11	0.21	Colombia	0.09	0.60
India	0.10	0.19	Philippines	0.09	0.60
Belgium	0.07	0.14	France	0.09	0.59
Croatia	0.06	0.12	South Africa	0.09	0.59
France	0.05	0.10	Dominican Republic	0.08	0.58
Serbia	0.05	0.10	United Kingdom	0.08	0.53
Romania	0.05	0.09	Paraguay	0.08	0.52
Austria	0.04	0.08	Mauritius	0.07	0.51
Germany	0.04	0.08	Nicaragua	0.07	0.49
Hungary	0.03	0.06	Guyana	0.07	0.48
Others	0.25	0.48	Others	0.84	5.73
World	51.95	100.00	World	14.59	100.00

Source: prepared by the authors with data from FAO (2019).

5. Conclusion

The fuel policies in Brazil are an important theme of study since new laws and market arrangements can generate consequences for consumers, producers, government, and the environment. This thesis highlighted the outcomes from Law No. 9,478 of 1997, the called Oil Law, on market power degree in the Brazilian oil industry. The key conclusion is that after more than 20 years from this policy, Petrobras is still the main oil company in the country, being the oil market characterized as a *de facto* monopoly.

In 2004, the Law No. 11,097 launched the National Biodiesel Production and Use Program (PNPB), determining an obligatory blend of biodiesel and petroleum diesel. This program expanded the biodiesel production obtained from soybeans and created new relationships between biofuels, fossil fuels, and food markets, bringing new challenges for soybean crushing plants regarding the production decision-making. In Brazil, prices of soybean grains, soybean meal, and soybean oil are decisive in biodiesel price formation, as well as biodiesel price is an important component for the blended diesel price. Biodiesel is an eco-friendly product, its demand is driven by the blend mandate policy, and the level of petroleum diesel consumption. Since blended diesel is a necessary good, we believe that the biodiesel sector presents great opportunities for new investments.

In 2017, the new pricing system of fossil fuels adopted by Petrobras aimed to add more flexibility to Brazilian fuel prices, letting them follow the international level. Additionally, in the same year, the National Biofuel Policy (RenovaBio) proposed the creation of a carbon credit market to boost biofuel production and mitigate greenhouse gas emissions. In this arrangement, fossil fuel producers must buy carbon credits issued by the biofuel industry. If combined, these fuel policies can affect social welfare and the level of GHG emissions. The RenovaBio policy can generate important effects in the Brazilian economy, such as the abatement of GHG emissions, the expansion of hydrous ethanol consumption, the reduction of gasohol production, and the growth of total welfare.

Therefore, the policies studied in this thesis tend to foster biofuel production, decreasing the Brazilian dependence on fossil fuels. The agricultural sector is an important beneficiary, mainly the agribusiness sectors of sugarcane and soybean. As a consequence of the greater use of biofuels, the level of pollution can decline if the cultivation of crops and the processing industry present lower levels of greenhouse gas emissions per liter of fuel.