WARM GLOBE, “WARMER” POLICIES: AN EMPIRICAL TEST OF THE GREEN PARADOX HYPOTHESIS

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ABSTRACT

We study the effect of an ethanol expansion on carbon emissions using Brazilian energy data from 1981 to 2018. We find that greater ethanol production provides a perverse incentive for Brazilian oil producers to increase their rate of oil extraction. We report that following a cubic meter rise in the one period lagged change in Brazil's ethanol production, change in oil extraction increases between 0.53 m^3 to 0.64 m^3 in the current period, a weak green paradox. These estimates translate into short-run and long-run elasticities of 1.5 and 4.9 respectively, implying that a one percent rise in the change in ethanol production now would increase change in oil production by 1.5 percent in the short-run and 4.9 percent in the long-run. Also, net CO_2 emission in Brazil is positive if the reduction in CO_2 emission as a result of substituting ethanol for oil on a one-for-one basis is less than 73 percent in the short run and 244 percent in the long run, thus, evidence for a strong green paradox. The results indicate that Brazil's well-intended ethanol policy may have resulted in detrimental outcomes that go against the objectives of the policy. We recommend that, at the very least, Brazil and other policymakers should critically evaluate a single policy such as an ethanol subsidy used in isolation to ascertain whether or not their implementations have the potential of increasing fossil fuel extraction and ultimately increasing CO_2 emissions now or in the future.

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DEDICATION

I dedicate this thesis to my parents: Mr. and Mrs. Sarpong, my sister Linda Acheampong and husband not forgetting my nieces Akua Akyaamaa Acheampong, Nana Yaa Afrakoma Acheampong, and Afia Nyamekye Acheampong.

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LIST OF ABBREVIATIONS

ADF	Augmented Dickey-Fuller
CO_2	Carbon dioxide
FFV	Flex-Fuel Vehicles
GHGs	Greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
MT	Million Tonnes
TOE	Tonnes of Oil Equivalent
VAR	Vector Autoregressive

Chapter 1

Introduction

The rise in the world’s temperature beyond the pre-industrial baseline has raised world governments' interest to tackle climate change in a more aggressive manner. The primary source of the world’s greatest public good problem (Sinn 2008) is the emission of greenhouse gases (GHGs). Since the start of the industrial era (around the 1750s), human-produced greenhouse gases such as carbon dioxide (CO_2), nitrous oxide, and methane have caused much of the observed increase in Earth's temperatures. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concludes that the main cause of climate change is through human activities and the principal gas contributing to global warming is CO_2. Much of the CO_2 released into the atmosphere is through fossil fuels (IPCC 1997).

During the 2015 United Nations climate conference in Paris, each member country communicated their “nationally determined contribution” toward the realization of limiting global warming. Brazil presented a biofuel policy that is aimed at reducing domestic GHG emissions by 37% by 2025 and 43% by 2030 (Dessureault and Zimmerman 2019). These targets were based on the 2005 domestic emissions level. To achieve these targets, the Brazilian government aims to increase biofuel consumption, increase the share of advanced biofuels, increase ethanol supply, and increase the share of biodiesel in the diesel mix. Specifically, Brazil plans to increase the share of sustainable biofuels in the Brazilian energy mix to about 18% by 2030 (Federative Republic of Brazil 2015). Also, Brazil targets 45% of renewables in its energy mix by 2030, including expanding the use of renewable energy sources as well as expanding the use of non-fossil fuel energy sources domestically.

A number of programs have been implemented to ensure the accomplishment of Brazil’s climate targets as well as boosting the growth of sugarcane ethanol. One of such programs is the ProAlcool program for ethanol initiated in 1975. The program is designed to capitalize on Brazil’s comparative advantage in the production of sugarcane, a major raw material for ethanol production. The main objectives of the program are to reduce the national dependence on oil imports, promote technical and industrial development through ethanol fuel production, and strengthen the sugarcane and sugar sectors (Johnson and Silveira 2014). As a result of Brazil’s long-standing national ethanol program, biofuels in Brazil accounted for about 25% of road transport fuel demand compared to less than 3.5% globally (IEA, 2015).

In 2017, Brazil instituted another “national biofuels policy” referred to as RenovaBio. In addition to contributing to the country’s commitment under the Paris Agreement, RenovaBio is aimed at promoting the production and use of biofuels in the national energy matrix. Through RenovaBio, Brazil provides preferential treatment for ethanol under both its Contribution for Intervention in Economic Domain and the Social Integration Program. In addition to the central government’s support, several other Brazilian states provide differential treatment for ethanol consumption through the use of state-level taxes for the circulation of goods and services (ICMS). For instance, while the ICMS tax charged on ethanol varies between 12 to 30 percent, the tax on gasoline ranges from 25 to 34 percent. To prevent ethanol imports and encourage local production, the Ministry of Development, Industry and Commerce (MDIC) imposed an annual tariff-rate quota (TRQ) of 600 million liters on ethanol imports. Imports above the quota are subject to the 20% Common External Tariff under the Mercosur agreement.[1]

While promoting local production and the use of biofuels particularly sugarcane ethanol in Brazil, ethanol produced is supplied to a very unique Brazilian market. The share of the Brazilian automotive market is dominated by one-liter engine cars, which in the 1990s became the symbol of the Brazilian automotive industry, reaching over 70% of sales in 2001 (Posada and Facanha 2015). Brazil continues to be amongst the largest automobile market worldwide and accounts for over half of all vehicles sold in Latin America (Posada and Facanha 2015). In addition, Brazil is the only country in the world with fuel stations that have at least one pump dedicated exclusively to pure hydrated ethanol (UNICA 2015). The passenger car market in Brazil is dominated by flex-fuel vehicles (FFV) that are designed to run on gasoline (E22), ethanol (E100), or any combination of both fuels (ICCT 2017). Starting in 1976, FFV owners faced flexibility in their choice of fuel as all filling stations in Brazil installed ethanol fuel pumps during the commencement of the ProAlcool program.

By mid-2010 about 70 FFV models were available in the market, and a total of 15 car manufacturers produced flex-fuel engines by the end of 2013.[2] This dominated all light vehicle

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[1] The Mercosur agreement is an international trade agreement between the European Union and Mercosur states - Argentina, Brazil, Paraguay and Uruguay.

[2] UNICA, 2010.

segments except sports cars, off-road vehicles, and minivans (Posada and Facanha 2015). As of December 2019, over 96% of the annual newly registered vehicles in Brazil were FFV (UNICA 2019a). While the fleet of flex-fuel cars has progressively increased over the years, the fleet of gasoline cars has consistently declined. The estimated Brazilian flex-fuel vehicles increased from 12 million fleets in 2010 to 30 million fleets in 2019 (UNICA 2020). During the same period, the fleet of vehicles that run on gasoline dropped from 13 million to 7.6 million (UNICA 2020).

Brazil's ProAlcool and RenovaBio programs demonstrate the regulatory efforts the country has made and continues to make to promote the consumption of biofuels and ultimately curb carbon dioxide emissions. As indicated by Grafton et al. (2012), the main stimulus to the use of biofuels is policies that encourage the substitution from fossil fuels, aided by supporting mechanisms, such as subsidies and tax exemptions. However, as Brazil and other world governments at large continue to adopt technologies that are low on carbon emissions, some evidence suggests that such well-intended policies may result in adverse, unintended consequences that contradict the very objective of such policies. This is the phenomenon popularly referred to as the green paradox.

One of the insights from the green paradox literature is that, similar to carbon taxes, the availability of a cheaper alternative to fossil fuels can trigger the phenomenon. As shown by Grafton et al. (2014) and van der Ploeg & Withagen (2012), a declining price of a substitute either as a result of technological progress or subsidies can result in a green paradox. Grafton et al. (2014) showed that US biofuel subsidies offered a pervasive incentive for fossil fuel producers to increase their rate of extraction, accentuating climate change damages. Similarly, Grafton et al. (2012) and Van Der Ploeg & Withagen (2012) reported that the combination of subsidies for renewable energy and the anticipation of cheaper renewable backstop technologies may induce an increase in the current rate of fossil fuel extraction.

Will Brazil's biofuel policy of encouraging the production and use of ethanol trigger a green paradox? This is the critical question we ask in this study given the fact that oil production in Brazil is hugely influenced by the state through Petrobras with little private sector involvement.[3] Directly or indirectly (through incentives/mandates), the government can influence or set both oil and ethanol production which contrasts other Green Paradox settings where we worry about what

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[3] The private sector activities increase due to the introduction of Concession Bidding Rounds, amendment of the Production Sharing Law, and Petrobras' decision to encourage divestment of both upstream and downstream assets.

oil producers will do following an incentive given to ethanol producers. To investigate whether this is a concern or not, we explore the unique Brazilian fuel market and construct and administer an empirical test of the green paradox hypothesis. Specifically, we test (1) if promoting the production of biofuels particularly ethanol in Brazil has encouraged fossil fuel producers to increase their current extraction rate (a weak green paradox) and (2) whether the increased production of ethanol through its implication on oil has resulted in higher CO_2 emissions, thus a strong green paradox.

Chapter 2

Brazil’s Ethanol Experience

With an estimated population of over 211 million people and a land size of 8.5 million km^2, Brazil is the second-largest producer of biofuels, behind the United States. Brazil’s experience with biofuels dates back to the 20th century. Nonetheless, the first global oil crisis in the 1970s (due to the oil shortage resulting from an oil embargo enacted by some members of OPEC) spurred the Brazilian government to initiate a large-scale biofuel program, specifically fuel ethanol. In responding to the crises, the Brazilian government decided to reduce the national dependence on imported oil and create domestic demand for its surplus sugarcane market. Hence, in 1975 the government of Brazil inaugurated the national ethanol program ProAlcool.

After the second oil-shock in 1979, the government decided to expand the program to provide support for large-scale hydrated ethanol producers to supply cheaper fuel. The program provided three drivers for ethanol as fuel (Goldemberg 2008). First, state-owned oil company Petrobras provided guaranteed purchases from sugarcane farmers, removing fears of lost investment. Second, the government provided soft loans for ethanol-producing firms. Lastly, the government ensured that ethanol at the pump fetched a price of at most 59% that of gasoline. These incentives from the program promoted the use of vehicles running on pure ethanol in Brazil in the 1980s.

Following the expansion, the first 16 Petrobras gasoline stations started supplying about two thousand ethanol adapted vehicles with neat hydrous ethanol. During the second half of 1979, the first modern commercial car to run exclusively on ethanol (E100), the Fiat 147, was launched (Bastos 2007). Other automobile factories were lured by the numerous ethanol incentives (such as tax incentives, the blending mandates, and subsidies for sugarcane expansion among others) provided by the Brazilian government to modify gasoline engines to support hydrous ethanol. This period marked the second phase of the ProAlcool program and was characterized by rapid growth in hydrated ethanol production and increased production of passenger vehicles with ethanol engines.[4] Soccol et al. (2005) report that "the rapid growth in hydrated ethanol production resulted in a large surplus of gasoline which had to be exported, forcing Petrobras to make costly changes to its oil refining structure".

In the early 1980s, hydrous ethanol became highly attractive to consumers primarily because of the Brazilian government's strategy to peg the pump price of hydrous alcohol at 64.5% of gasoline price (Goldemberg 2008). This led to a significant rise in registration (Figure 2.1) and sales of vehicles with neat-ethanol engines, occupying more than 90% shares of overall vehicle sales (Cortez et al., 2016). Goldemberg (2008) reports that the total fleet of neat-ethanol fuelled vehicles reached 5 million. Several service stations had reservoirs to service engines that run on solely anhydrous ethanol as well as ethanol-gasoline blends at 20% to 25% ethanol. However, there remained uncertainty in the ethanol market, mainly because neat-ethanol vehicle owners could not use their vehicles in neighboring countries and in some Brazilian regions which did not have service stations equipped to supply pure ethanol (Goldemberg 2008). Also, there were doubts about whether the expanding ethanol demand could be met by producers.

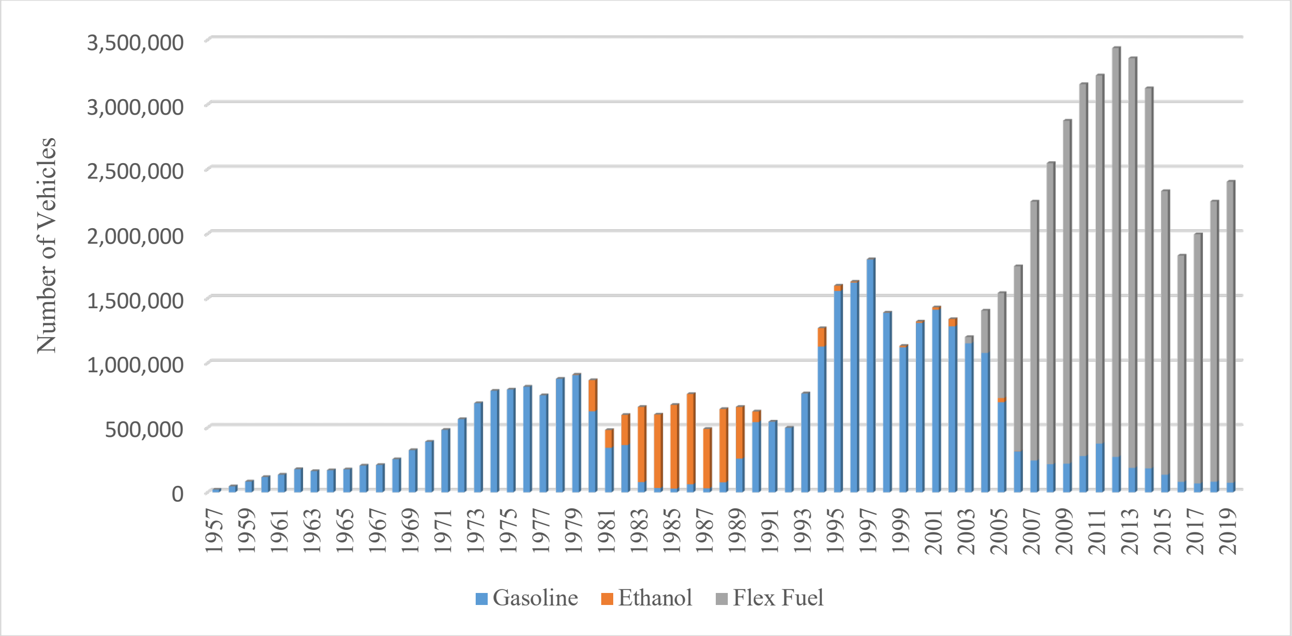

Figure 2.1. Registration of new vehicles by fuel type

Source: ANFAVEA (2020)

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[4] These vehicles could only burn ethanol and are different from flex vehicles (able to run on more than one fuel). There are two types of ethanol, hydrous and anhydrous. Hydrous (or wet) ethanol is the most concentrated grade of ethanol and is used in E100 vehicles. Anhydrous ethanol, however, is mixed with variable proportions of gasoline up to 25% (Cruz, Souza, and Cortez 2014). See also Figure 2.2 for further information.

The credibility of ProAlcool began to fall during the third phase of the program in 1986. The period was characterized with the shortage of ethanol amidst the rapid increase in ethanol-fuelled vehicles, political uncertainty (resulting from the end of the Military Government and the implementation of the New Republic Regime), low costs of oil on the international market, low domestic price of ethanol, high international sugar price, low cost of imported ethanol and methanol from the USA among others (Soccol et al., 2005; Cortez et al., 2016). This resulted in stagnation and affected the credibility of the program. The stagnation caused the fleet of passenger vehicles fuelled by pure ethanol to drop from 94% in the middle of the 1980s (apex of the alcohol era) to about 51% in 1989 (Soccol et al., 2005; Rosillo-Calle & Cortez, 1998). However, the increased anhydrous ethanol blending mandate ensured that the total ethanol demand was maintained.

In the early 1990s, many vehicle users gradually abandoned the use of ethanol-powered vehicles due to ethanol shortages and inadequate ethanol service stations (ANFAVEA 2019). Annual hydrous ethanol production reduced significantly between 1995 and 2000 (the fourth phase of ProAlcool), declining by half from a total volume of 10 billion liters to 5 billion liters (Empresa de Pesquisa Energetica (EPE) 2015). The sugarcane surplus production was channeled to the production of sugar and anhydrous ethanol. The consumption of anhydrous ethanol continued to increase due to the blending mandate and the increased sales of gasoline vehicles. Also, the tonnes of Brazilian sugar exported increased significantly from 0.8 million in 1990 to 7.48 million after a decade, contributing to a decline in sugar price on the international market from 316.7 US$/t to 192.1 US$/t (MAPA, 2011). During this period, the Brazilian government liberalized the prices of anhydrous and hydrous ethanol in 1997 and 1999 respectively from the 64.5% cap. A year after liberalizing the price of hydrous ethanol, the government deregulated the sector and ended the subsidy for hydrous ethanol (Giacomazzi 2012; Valdes 2011).

Aiming to restructure the sector and take advantage of Brazil's comparative advantage in sugarcane production, various associations consisting of sugarcane mills and producers joined efforts to define the sector's interests. In 1997, the efforts of these associations resulted in the formation of União da Indústria de Cana-de-Açúcar (UNICA), mandated to establishing a competitive sugar-energy sector capable of competing globally and sustainably in the production of ethanol, bioelectricity, and sugar (Cortez et al. 2016). The organization remains the largest representative organization for Brazil's sugar and ethanol sector and is responsible for about 60%

of overall sugar production and more than 50% of all ethanol produced in Brazil. Largely, the organization has been successful by far. However, the Brazilian sugarcane industry is still characterized by uncertainty in sugarcane yield – the main feedstock in Brazil's ethanol production due to the crop's high sensitivity to weather conditions.[5]

In 2000, the state of São Paulo reduced the state tax and provided an incentive for ethanol production (Cortez et al., 2016; Rosillo-Calle & Cortez, 1998). Around the same period, the Federal Government also demonstrated great interest in ethanol and its potential for the future. This period marked phase five of ProAlcool, the era of flex-fuel vehicles. The introduction of flex-fuel vehicles in 2003, revived the vehicle and fuel industries, turning a new phase of expansion for the ethanol industry (Cortez et al. 2016). Ethanol production saw a massive boost in this period (Figure 2.1). Flex-fuel vehicles eliminated the problems consumers initially faced since they can run on blends from E0 to E100. These engines were built with an intelligent control system that could recognize the ethanol and gasoline levels in the fuel and automatically self-calibrate for the best possible operation (Goldemberg 2008).

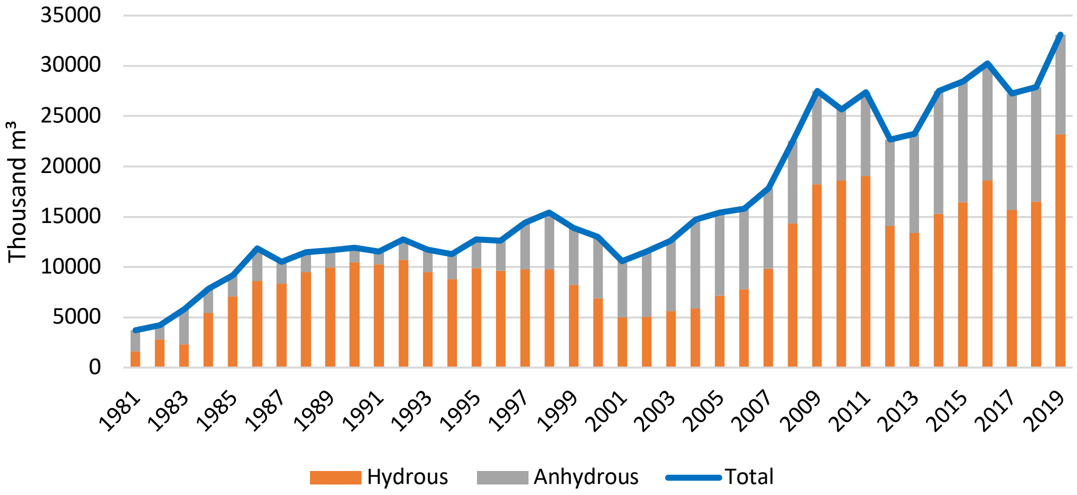

Figure 2.2. Evolution of ethanol production in Brazil

Source: UNICA, 2019b

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[5] More of this developments are covered extensively in the Oil and Gas Year Brazil 2019 published in collaboration with the Rio de Janeiro State Federation of Industries (Firjan) and Brazil's National Agency of Petroleum, Natural Gas and Biofuels (ANP); Petrobras "Annual Report 2018"; and BP Statistical Review of World Energy 2019.

Flex-fuel vehicle owners have the flexibility to decide which type of fuel to use based on personal preference and the relative pump prices of hydrous ethanol and gasoline. Most flex-fuel vehicle owners switch to hydrous ethanol when their relative price is lower than 70% of gasoline price (Cruz, Souza, & Cortez, 2014; Nogueira & Capaz, 2015). Nogueira & Capaz (2015) assert that flex-fuel vehicle owners consider the ratio of ethanol and gasoline prices when making their purchasing decision. "After considering the differences in heating value and efficiency when using these fuels, consumers have assumed the indifference price of ethanol as 70% of gasoline price" (Nogueira & Capaz, 2015). Using revealed preference approach, Salvo and Huse (2013) observed that about 20% of FFV users choose gasoline when the pump price of gasoline is 20% above the price of ethanol in \$/km terms. Likewise, 20% of FFV users choose ethanol over gasoline when ethanol is priced 20% above gasoline in \$/km terms. However, Cruz, Souza, & Cortez (2014) advise that there is a need to educate FFV owners to take into consideration the positive externalities of ethanol and not only the relative prices of alternative fuels.

The consumption of hydrous ethanol has increased in recent years while gasoline has dropped (UNICA 2020). About 17% of Brazil's energy needs are provided by sugarcane and over 40% of Brazil's gasoline needs have been replaced by sugarcane ethanol. Between 2009 and 2018, the total fleet of ethanol vehicles in Brazil more than tripled while the gasoline fleet of vehicles dropped by 40% (Ibid). As of 2018, out of the 37.5 million estimated Brazilian automobile and light vehicle fleet, 76% (28.6 million) were FFVs while gasoline-only and ethanol-only vehicles made up 22% (8 million) and 1% (half a million) respectively of the total (Ibid). Also, 87.4% of newly registered vehicles in 2019 were flex-fuel (ANFAVEA 2019).

The introduction of FFVs coupled with the ethanol-gasoline blending mandate has created a demand for Brazil's sugarcane ethanol (Cortez et al. 2016). Since the introduction of ProAlcool until the third phase in 1992, the mandatory blending mandate of ethanol fuel with gasoline fluctuated between 10% and 22%. Currently, Brazil's ethanol blend requirement in gasoline is 27% (Table 2.1), and a gradual rise in biodiesel blends from 8% (B8) 2017, to 9% (B9) in 2018, and it's currently set at 10% (B10) since March 2019. The percentage of the ethanol blend is based on sugarcane harvest in a particular season and the production levels of sugarcane ethanol, resulting in blend variations even within the same year.

Table 2.1. Historical evolution of ethanol blending mandates in Brazil

Year	Ethanol Blend	Year	Ethanol Blend	Year	Ethanol Blend
1931	E5	1993-1998	E22	2008	E25
1976	E11	1999	E24	2009	E25
1977	E10	2000	E20	2010	E20-25
1978	E18-20-23	2001	E22	2011	E20-25
1981	E20-12-20	2002	E24-25	2012	E20
1982	E15	2003	E20-25	2013	E20-25
1984-1986	E20	2004	E20	2014	E25
1987-1988	E22	2005	E22	2015	E25-27
1989	E18-22-13	2006	E20-25	2016	E27
1992	E13	2007	E23-25	2019	E27

Source: Rico (2007), Table 3.8, Pg. 81–82; USDA GAIN (2019), Pg. 5.

As of 2015, Brazil had 383 installed ethanol mills (362 were in operation while 21 had operating permission – but were not operating). The total capacity of ethanol production (both hydrous and anhydrous) in that period stood at approximately 38 billion liters per year (Cortez et al. 2016). In 2019, domestic ethanol production was 33,102.91 thousand m^3 (Figure 2.2) with domestic consumption accounting for over 80% of total production. Brazil imported an additional 9,168 thousand m^3 of ethanol for approximately $602 million (ANFAVEA 2019). However, the ethanol export volume in the same period stood at 12,158 thousand m^3 generating revenue to the tune of $993 million (ANFAVEA 2019). Currently, about 10 million hectares representing approximately 12% of total farmed hectares (which translates into 1.2% of Brazil's total land area) is used for the cultivation of sugarcane (UNICA 2019b), the main ingredient for Brazil's ethanol.

Although the success of Brazil's ethanol policies is subject to debate, it is generally accepted that the policies have resulted in a positive environmental impact (Rosillo-Calle & Cortez, 1998), however, there is little empirical evidence to support it. The environmental impact of the series of "green" policies are yet to be adequately assessed both at the production and consumption levels. Ethanol is widely accepted to lower carbon dioxide emissions relative to fossil fuels (Hill et al., 2006 and Farrell et al., 2006) however, the processes leading to the extraction of the final product such as burning sugarcane fields, a common practice in Brazil remains a major concern due to the adverse environmental and health implications. To confidently assess the effectiveness of Brazil's ethanol policies in terms of their impact on climate change, an empirical investigation is essential. Consequently, this study investigates the Brazilian fuel market and provides empirical support for the effectiveness of Brazil's ethanol policies on carbon emissions.

2.1 Literature Review

The green paradox originates from the supply response from fossil resource owners following a policy change that threatens their profitability. The Hotelling rule—that for non-renewable resources, the net price (market price less marginal cost) must rise at the rate of any interest-bearing instrument such as the rate of interest in a competitive market—forms the theoretical core for analyzing the green paradox and non-renewable resources at large. Named after Harold Hotelling in his 1931 paper "The economics of exhaustible resources," the rule has been used by economists as a theoretical and conceptual framework for analyzing the long-run evolution of prices and supplies of non-renewable resources. The rule assumes that non-renewable resource owners operate in an efficient market (with no sources of market failure), enjoy scarcity rents, and maximize their profits by deciding when to extract their resource whose complete stock is known.

However, in practice, the resource stock is unknown. In his book *The Growth Spiral*, Binswanger (2013) surmises that Hotelling only considered extraction, which reduces the stock of reserves and completely ignored exploration which increases the stock of reserves. In Hotelling's simple model, extraction cost had no tendency to rise irrespective of the depth of extraction. However, in reality, the cost of extraction increases (referred to as the degradation effect) as owners continue to dig deeper to get more of the resource out of the ground. The degradation effect may cause a decline in the scarcity rent, and a stronger degradation effect may completely erode all the scarcity rent, resulting in economic exhaustion—a situation where the cost of further extraction becomes higher than the market is willing to pay (Livernois, 2009).

There are several extensions to the original Hotelling (1931) rule that address the limitations of the original rule[6](Slade and Thille 2009). Most relevant to this study is the extension to the monopoly setting where rent is now defined as marginal revenue minus marginal cost, instead of price minus marginal cost in a competitive market setting. In general, monopolists will sit on

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[6] Slade and Thille (2009) indicate a number of extentions that have been added to the orignial Hotelling (1931) rule.

their stock longer to maximize profits relative to the competitive firm. This provides a theoretical basis for understanding Petrobras' behavior in the Brazilian context.

Fossil fuel use results in carbon emissions, a serious external cost that most climate policies attempt to address, again ignored in the simple Hotelling model. Furthermore, technological advancement and the impact of alternative energy sources receive no consideration in the traditional Hotelling model. In general, the Hotelling rule implies that extraction diminishes the stock of fossil reserves and price rises to reflect both rising scarcity and marginal extraction cost, a pattern that is to a large extent, difficult to reconcile with historical data and is notoriously at odds with reality which has invited several criticisms.[7] Sinn (2015) reports that the real oil prices in the mid-2015 reflected the hikes in oil prices that occurred before mid-1979—the oil price hike leading to the second oil crisis. Nonetheless, insights from the theory remain useful in analyzing how the market for non-renewable natural resources will evolve.

Sinn (2008) ignited the debate and research into the green paradox phenomenon. He and many others regard carbon emissions as the world's greatest market failure and largest public goods problem and recognize the efforts governments are making to address the issue.[8] However, the author's discontent stems from the fact that the efforts aimed at reducing carbon emissions have largely focused on reducing the demand for fossil fuels—ignoring the supply side of the problem. According to Sinn (2008), CO_2 concentration in the atmosphere depends on extraction which occurs as a result of the interaction of demand and supply. Focusing solely on the demand for fossil fuels and ignoring supply is ineffective. Sinn (2008) argues that the efforts made by abating countries (such as countries signatory to the 2005 Kyoto protocol) to curb carbon emissions only reduce the discounted value of carbon price in the future more than the present, incentivizing resource owners to bring forward the extraction of their resources as a result of the anticipated price cut. He cautions that until demand reducing measures are matched by supply reducing ones, efforts to mitigate greenhouse effects will amount to little.

Like Sinn (2008), Green and Denniss (2018) admonish that policymakers ought to augment demand-side policies with supply-side policies to achieve greater efficiency. The authors explain that restrictive supply-side policies, such as fossil fuel subsidy reduction, fossil fuel supply tax or

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[7] For more thorough discussion, see the first systematic analysis by Barnett & Morse (1963); as well as Livernois (2009); and Gaudet (2007).

[8] See also Kunzig & Broecker (2008); Sinclair(1992); Nordhaus (1991); IPCC (1997); Stern & Stern, (2007), etc.

ban/moratorium, and fossil fuel production quotas, have lower monitoring, reporting, and verification (MRV) cost. They contend that unlike demand instruments that require detailed and complex regulatory institutions for MRV, restrictive supply policies target a relatively slim market of upstream fossil fuel providers whose output (especially coal and oil) are easy to measure and capture a wider coverage including downstream consumers. They add that in addition to the economic benefits associated with supply-side policies, they also result in political benefits such as greater public support, higher perceived benefits, higher perceived distributional fairness, and lower perceived costs.

Responding to the supply-side policies, several countries have encouraged the substitution away from fossil fuels towards renewable energy by promoting biofuel production via tax exemptions and subsidies. Although renewable energy sources such as biofuels are low on carbon emissions and solar and wind do not contribute to emissions (beyond those required for mill and panel production), they may in some instances generate perverse outcomes that contradict the objectives which justify their use. Grafton et al. (2012) theoretically show that renewable energy subsidies may lead to a green paradox. Given the assumptions that the renewable resource is produced under increasing marginal cost and both types of fuels are supplied in the market, they show that subsidies for the renewable energy result in a direct and indirect effect that oppose each other. A subsidy for the renewable substitute reduces the production cost and makes the substitute relatively cheaper leading to a reduction in the demand for fossil fuels, thus, a direct effect. The indirect effect is the increase in the demand for fossil fuels that arise from the reduction in the equilibrium price for fossil fuel. The net effect will depend on the curvature of the demand curve for energy and the supply curve for biofuels.

Theoretically, van der Ploeg & Withagen (2012) also show that subsidizing clean and expensive backstop technologies such as solar and wind energy leads to a rapid depletion of fossil fuels which results in greater climate change damages. Similarly, Gerlagh (2011) analyses how different assumptions underlying the extraction cost of fossil energy and a backstop technology affect the green paradox. He distinguishes between a weak and a strong green paradox. A weak green paradox occurs when biofuel production promotes greater fossil fuel extraction whereas a strong green paradox occurs when clean energy technology increases the net carbon emissions. In his first model, he assumes a fixed resource with a constant extraction cost and a perfect backstop technology. In the two remaining models, extraction cost is assumed to increase but the backstop in model 2 is assumed to be a perfect substitute whereas model 3 relaxes the perfect substitute assumption. The green paradox is stronger in the first model and erodes step by step through to third model.

The implication of the result by Gerlagh (2011) is similar to that of van der Ploeg & Withagen (2012) and Fischer & Salant (2012) who suggest that, in the absence of a carbon tax, a strong green paradox can be avoided if subsidies for clean backstop technology are sufficiently high enough to make the cost of clean energy lower than the extraction cost of fossil fuels.

Strand (2007) considers the adverse effects of a “technology treaty” that is signed in the absence of other measures as carbon taxes or quotas. The author introduces uncertainty regarding the discovery of a clean backstop technology after a treaty is signed and assumes that the marginal cost of the backstop technology is lower than the extraction cost of fossil fuels. The model results show two opposing effects which the author classifies as the immediate extraction and the extraction-moderating effects. The immediate extraction effect which results in a (weak) green paradox occurs when a “technology treaty” increases the probability of the resource (fossil fuels) becoming redundant, causing producers of fossil fuels to increase extraction more rapidly leading to greater carbon emission. On the other hand, the extraction-moderating effect occurs as the positive rate of developing and adopting clean technology displaces fossil fuels use and reduces expected emissions.

Grafton et al. (2014) further developed the analysis by showing using US energy data that substituting cheaper low carbon energy for fossil fuels results in a green paradox. Like Gerlagh (2011) and Grafton et al. (2012), they decompose the total effect into a weak and a strong green paradox. They establish the existence of both a weak and a strong green paradox. Specifically, they find that (1) a 1% rise in US biofuel production increases US fossil fuels production by 0.04% (weak green paradox) and (2), a strong green paradox occurs if CO_2 emission reduction based on a one-for-one substitution of biofuels for fossil use is below 26% in the short-run and 57% in the long-run. The result implies that incentivizing the production of biofuels and to a larger extent renewable energy through the provision of subsidies lead to greater environmental damages (a green paradox). This occurs since fossil fuel suppliers anticipating a future increase in the production of alternative energy increases current extraction, leading to a front-loading of GHG emissions.

Before the implementation of most of these environmental policies especially a carbon tax, they are pre-announced to give economic agents time to adapt to the policy change. Di Maria et al. (2012) document evidence of environmental policies that have significant unavoidable time lags and outline reasons for their occurrence. Evidence shows that the existence of an implementation lag in some major environmental policies such as the US Clean Air Act Amendments affected emissions. For instance, Di Maria et al. (2012) show using analytical models that implementation lags embedded in Title IV of the 1990 US Clean Air Act Amendments affect the rate of emissions. In addition to their theoretical predictions, their empirical findings reinforce the adverse effect arising from implementation lags. Their findings reveal that, in the absence of implementation lags, sulfur dioxide (SO_2) emissions associated with coal-fired power plants in the US would have been 9% less than actual emissions.

Following these results, Di Maria et al. (2014) provide a more detailed empirical test of the green paradox hypothesis by focusing on the Acid Rain Program. The authors examine the price and use (demand) effects of a cap on the allowable volume of SO_2 emissions that are announced in time $t = 0$ but implemented in a later period. The announcement of a future ceiling on SO_2 emissions following the passing into law of the 1990 CAAA[9] generates two broad outcomes resulting from the supply shift. First, there is a resulting price reduction in coal. Second, no evidence for a quantity response (increase in the sulfur content of coal) following the reduction in coal prices was found. However, by considering procurement strategies, they found evidence of a green paradox among a subgroup of power plants that rely largely on the spot market. The mixed results provide little evidence for the existence of the green paradox.

On the other hand, Lemoine (2017) found evidence for the green paradox resulting from the breakdown of the carbon cap and trade legislation in the U.S Senate in 2010. The author reports that, contrary to the proposed aim of the legislation, carbon emissions increased by over 12 million tons between the period discussions on the legislation commenced and the time the legislation was defeated. He reports that, even before the collapse of the bill, expectations of a possible future cap had already been formed leading to a drop in the prices of coal and natural gas.

Like the preceding studies, Smulders, Tsur, & Zemel (2012) employ a closed-economy

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[9] The Act "seeks to protect human health and the environment from emissions that pollute ambient, or outdoor, air. It requires EPA to establish minimum national standards for air quality, and assigns primary responsibility to the states to assure compliance with the standards"(CRS 2020).

continuous-time model to study the effect of a pre-announced carbon tax. However, they deviate from the assumption of fossil energy scarcity and show that a carbon tax policy announced in advance results in unintended consequences in the interim as consumers smooth their consumption path by increasing early investment in fossil energy and increasing emissions, which is contrary to the intended purpose of the announced policy. The authors show that households respond to a future reduction in fossil energy production and use by reducing consumption and increasing savings in the interim phase to invest in capital. This consumption smoothing motive gives rise to the build-up of larger capital stock, and since capital and energy are complements, the announcement of the carbon tax instead increases emissions during the interim phase.

According to Smulders, Tsur, & Zemel (2012), the adverse unintended effect is identical whether the implementation time is known with certainty or not. They again show that a green paradox occurs whether a high tax rate that is capable of altering the behavior of resource users toward the use of solar energy or a mild tax rate that does not induce a switch from polluting (fossil fuels) to clean energy sources (solar) is set. However, they note that the key driver of the interim behavioral change before the implementation of the carbon policy is not the carbon tax in particular but rather the anticipated reduction in fossil energy use. Similar to the announcement effects, Strand (2007) shows using simulations that a "technology treaty" favoring clean technology signed at a period in time and adopted at a later period at all times increases cumulative extraction.

A declining price of a substitute for fossil fuels and the presence of an implementation lag related to environmental policies are not the only possible causes of a green paradox but also the time profile of a carbon tax. The imposition of a carbon tax is largely used by countries as an alternative policy measure, and sometimes as a complementary policy to clean energy subsidies to increase the price of fossil fuels and encourage the switch to renewable energy and ultimately reduce emissions. However, the imposition of a carbon tax does not automatically guarantee a reduction in emissions, as emissions may increase if the tax is not optimally designed.[10] It is therefore important to design an optimal tax that is aimed at encouraging a switch to "green" technologies to enjoy the full benefits of these complementary policies.

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[10] For more insight on the optimal design of carbon taxes see also Chakrovorty et al. (2006), Tahvonen (1997) and, Hoel and Kverndokk (1996).

Hoel (2010) demonstrates that given reasonable assumptions on expectation formation, a higher present carbon tax will achieve the intended effect of reducing present carbon emissions. However, the author argues that a rapidly rising carbon tax may result in a green paradox as resource owners shift the extraction path to the present thereby increasing near-term emissions. Sinn (2008) makes a similar observation by stating that a sufficiently rising carbon tax only induces resource owners to sacrifice future extraction for the present, leading to a green paradox. Ulph & Ulph, (1994) also show numerically that the optimal emission tax is not a continuous upward rising curve but an inverted U-shaped curve. They show that an initial upward rising emission tax followed by an eventual fall is more effective in reducing the extraction rates of fossil fuels, contrary to the argument advanced by Sinclair (1992) for a falling ad valorem carbon tax.

For the United States, Davis and Kilian (2011) found that a 10% rise in carbon tax reduces carbon emissions from vehicles by 1.5%. Andersson (2019) found a much higher carbon tax elasticity for Sweden. His result showed that following a 1% rise in the carbon tax, carbon emissions from transport reduced by 11% and the carbon tax elasticity of gasoline demand is three times the price elasticity. Rivers and Schaufele (2015) showed that a carbon tax in the Canadian province of British Columbia yields a large consumer response to demand than market price movements. Over the first four years of British Columbia's carbon policy, carbon emissions from gasoline consumption in the province reduced by 2.4 MT of CO_2 equivalent. On the contrary, Pretis (2019) showed that British Columbia's carbon tax "has not 'yet' led to a statistically significant reduction in aggregate CO_2 emissions"

While these results provide evidence for the effectiveness of a carbon tax, Andersson (2019) advises that estimating the effect of a carbon tax on changes in demand for gasoline must be done with caution. He asserts that unlike the United States and Canada, in Europe, diesel is used as engine fuels for most passenger vehicles. Therefore, failing to draw a clear distinction between the effect of a carbon tax on all forms of fossil fuels and gasoline alone may result in estimation problems. He identifies shortfalls in the studies by Rivers and Schaufele (2015) and Davis and Kilian (2011), as they fail to account for substitution between fuels as well as the different modes of transport.

As the literature review has shown thus far, a green paradox may occur under different policy scenarios and assumptions. Different policy measures have been adopted to reduce carbon emission. However, none of these policy approaches has adequately resolved the world's greatest public good problem. Subsidies to alternative energy sources, pre-announced climate policies, and carbon taxes sub-optimally designed can alter the extraction path of fossil fuels, shifting emissions to the present. Although there have been numerous policy approaches, empirically, there is limited research attempting to provide evidence for the existence of a green paradox. Researching the green paradox will require long consumption, production, and emissions data on fuels that are mostly scarce or unavailable. Consequently, a number of these studies (as outlined in the review) have adopted the use of analytical models and simulation approaches to show when the green paradox occurs in theory under different climate policy scenarios. This study bridges the gap in the literature by using long Brazilian fuel data to provide an empirical test rooted in previously developed theory.

2.2 The effect of an incentive for ethanol on the supply of oil

After Sinn (2008) spurred the green paradox debate and advocated that climate policies must not only look at the demand but also incorporate the supply-side, some stakeholders (such as the IPCC, governments, and researchers) are now giving at least as much weight to the supply side as to the demand side of the market. Several polices ranging from subsidies for clean technology and its development to blending mandates have been adopted by policymakers. For instance, in Brazil, the ProAlcool program provides several incentive packages to sugarcane farmers, ethanol producers, and consumers that encourage the substitution away from fossil fuels towards biofuels.

In this section, we develop a theoretical model by first assuming a general supply function for oil which is obtained from the profit maximization problem of oil producers. We further assume that oil and ethanol are both supplied in a competitive market—consumers have adequate information and can compare the relative prices of oil and ethanol before making their purchasing decision. We specify our supply function as $Q_S = S(P_O, P_{ES}, P_N, I_O)$, where Q_S and P_O are the supply and price of oil, P_N captures the price of other non-ethanol substitutes for oil such as coal and natural gas and I_O represents the input price of oil producers. The supply function for oil is upward sloping, thus, $\partial S/\partial P_O > 0$. We allow oil supply to be influenced by any incentive provided for alternative cleaner fuels such as subsidies for ethanol through a price mechanism indicated by P_{ES}. Thus, P_{ES} is the price of ethanol that incorporates the subsidy for ethanol producers, implying that $P_{ES} = f(P_E, \Gamma)$. We define P_E as the price of ethanol without an incentive and Γ as a supply induced incentive for ethanol such as a subsidy. The supply function is now specified as $Q_S = S(P_O, P_{ES}(P_E, \Gamma), P_N, I_O)$.

On the demand side, we assume a given demand which is a function of output prices and income and is specified as $Q_D = D(P_O, P_E, P_N, z, Y)$. Q_D is the demand for oil with a slope $\partial D / \partial P_O < 0$, i.e. a downward slopping demand curve, z, and Y represent the price of consumers' composite commodities[11] and income respectively. All other variables remain as already defined. For simplicity, we normalize the price of the composite commodity to one. The demand function reduces to $Q_D = D(P_O, P_E, P_N, Y)$.

Using the equilibrium condition $Q_D = Q_S = D(P_O, P_E, P_N, Y) = S(P_O, P_{ES}(P_E, \Gamma), P_N, I_O)$ we redefine P_O so that it is implicitly defined by the equilibrium condition. $P_O$will adjust to ensure that the equilibrium condition is satisfied, and it will be a function of only exogenous parameters, i.e. P_E, P_N, I_O, Γ, and Y. Thus, the equation defines the equilibrium oil price as a function of the price of ethanol, the price of other substitutes, input price of oil, an ethanol subsidy and income. In other words, we obtain an implicit equilibrium price expressed as $P_O = P_O(P_E, P_N, I_O, \Gamma, \mathrm{Y})$.

The equilibrium quantity (Q) obtained from the equilibrium condition after incorporating equilibrium price is

$Q = D[P_O(P_E, P_N, I_O, \Gamma, \mathrm{Y}), P_E, P_N, Y] = S[P_O(P_E, P_N, I_O, \Gamma, \mathrm{Y}), P_{ES}(P_E, \Gamma), P_N, I_O]$.

The resulting equilibrium quantity for oil implies that an ethanol subsidy has multiple effects. Thus, aside from its direct effect on both demand and supply, it indirectly influences supply and demand through its influence on the equilibrium price.

Since $D \equiv S$, and the objective of this study is to evaluate the effect of ethanol production (triggered by an ethanol subsidy) on the supply of oil, we restrict our computation to the equilibrium quantity obtained from the supply function. The total derivative of the function yields the outcome

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[11] Based on the composite commodity theorem, any group of goods whose prices move together can be treated as a single commodity. This makes it conveniently to examine one specific good and its relationship to "all the other goods". In this specific case, we capture the price of "all the other goods" except oil, ethanol and non-ethanol substitutes as t.

$$\frac{dQ}{d\Gamma} = \left(\frac{\partial S}{\partial P_O} \times \frac{dP_O}{d\Gamma}\right) + \left(\frac{\partial S}{\partial P_{ES}} \times \frac{dP_{ES}}{d\Gamma}\right) \tag{2.1}$$

To appropriately sign the effect of Γ on the equilibrium quantity of oil (i.e. $dQ/d\Gamma$), we further compute for $dP_O/d\Gamma$ to establish the relationship between Γ and P_O. If we let the function f be defined as the left-hand side of $S - D \equiv 0$ in equilibrium, the implicit function theorem states that we can obtain the comparative static $dP_O/d\Gamma$ with the following:

$$\frac{dP_O}{d\Gamma} = -\frac{df/d\Gamma}{df/dP_O}$$

$$\frac{dP_O}{d\Gamma} = -\frac{\frac{\partial S}{\partial P_O} \times \frac{dP_O}{d\Gamma} + \frac{\partial S}{\partial P_{ES}} \times \frac{dP_{ES}}{d\Gamma} - \frac{\partial D}{\partial P_O} \times \frac{dP_O}{d\Gamma}}{\frac{\partial S}{\partial P_O} - \frac{\partial D}{\partial P_O}}$$

If we multiply both the numerator and denominator terms by P_O/Q, we obtain:

$$\frac{dP_O}{d\Gamma} = -\frac{\left(\frac{\partial S}{\partial P_O} \times \frac{dP_O}{d\Gamma} + \frac{\partial S}{\partial P_{ES}} \times \frac{dP_{ES}}{d\Gamma} - \frac{\partial D}{\partial P_O} \times \frac{dP_O}{d\Gamma}\right)\frac{P_O}{Q}}{\left(\frac{\partial S}{\partial P_O} - \frac{\partial D}{\partial P_O}\right)\frac{P_O}{Q}}$$

We can sign the effect of Γ on the equilibrium price of oil using primitive assumptions, i.e. the assumed nature of the supply and demand functions (along with the relationship between P_{ES}, P_O and Γ). However, we find it helpful to express the comparative static in elasticity form, which we do by multiplying by creative versions of one:

$$\frac{dP_O}{d\Gamma} = -\frac{\left(\frac{\partial S}{\partial P_O} \times \frac{dP_O}{d\Gamma}\right)\frac{P_O}{Q} \times \frac{P_O}{P_O} \times \frac{\Gamma}{\Gamma} + \left(\frac{\partial S}{\partial P_{ES}} \times \frac{dP_{ES}}{d\Gamma}\right)\frac{P_O}{Q} \times \frac{P_{ES}}{P_{ES}} \times \frac{\Gamma}{\Gamma} - \left(\frac{\partial D}{\partial P_O} \times \frac{dP_O}{d\Gamma}\right)\frac{P_O}{Q} \times \frac{P_O}{P_O} \times \frac{\Gamma}{\Gamma}}{\left(\frac{\partial S}{\partial P_O} - \frac{\partial D}{\partial P_O}\right)\frac{P_O}{Q}}$$

$$= -\frac{\left(\frac{P_O}{\Gamma}\right)\left[\epsilon_{S,P_O}\epsilon_{P_O,\Gamma} + \epsilon_{S,P_{ES}}\epsilon_{P_{ES},\Gamma} - \epsilon_{D,P_O}\epsilon_{P_O,\Gamma}\right]}{\epsilon_{S,P_o} - \epsilon_{D,P_o}} \tag{2.2}$$

We simplify Equation 2.2 in the next two steps by first factorizing and cancelling out common terms.

$$\frac{dP_O}{d\Gamma} = -\frac{\left(\frac{P_O}{\Gamma}\right)\left[\epsilon_{P_O,\Gamma}(\epsilon_{S,P_O} - \epsilon_{D,P_O}) + \epsilon_{S,P_{ES}}\epsilon_{P_{ES},\Gamma}\right]}{\epsilon_{S,P_o} - \epsilon_{D,P_o}}$$

$$\frac{dP_O}{d\Gamma} = -\left(\frac{P_O}{\Gamma}\right)\left[\epsilon_{P_O,\Gamma} + \frac{\epsilon_{S,P_{ES}} \times \epsilon_{P_{ES},\Gamma}}{\epsilon_{S,P_o} - \epsilon_{D,P_o}}\right] \tag{2.3}$$

Since ethanol and oil in Brazil are regarded as substitutes, we expect a negative cross-price elasticity between oil supply and ethanol price, thus, $\epsilon_{S,P_{ES}} < 0$. Under the Hotelling rule, forward-looking oil owners alter their extraction behavior by bringing their extraction path forward following the implementation of policies that threaten their future resource-derived revenues. Therefore, the implementation of an ethanol subsidy that threatens the future profitability of oil producers will cause them to increase current extraction, putting downward pressure on oil prices. Grafton, Kompas and Long (2012) further show that an ethanol subsidy will lower not only the price of oil but also the price of ethanol at each point in time, hence, a negative cross-price elasticity between ethanol subsidy and price of ethanol (i.e. $\epsilon_{P_{ES},\Gamma} < 0$).

From our earlier assumption of the curvature of the demand and supply curves, own-price elasticity of supply (ϵ_{S,P_o}) and own-price elasticity of demand (ϵ_{D,P_o}) are given as positive and negative respectively. Equation 2.3 reduces to:

$$\frac{dP_O}{d\Gamma} = -\frac{P_O}{\Gamma}\left[\epsilon_{P_O,\Gamma} + A\right] \tag{2.4}$$

where the term $A = (\epsilon_{S,P_{ES}} \times \epsilon_{P_{ES},\Gamma})/(\epsilon_{S,P_o} - \epsilon_{D,P_o}) > 0$.

From Equation 2.4, we can observe that two scenarios arise depending on the relative magnitudes of $\epsilon_{P_O,\Gamma}$ and the A term. If $\epsilon_{P_O,\Gamma}$ is greater than A we have $dP_O/d\Gamma > 0$, otherwise it is negative. This implies that, we cannot provide a specific sign for $dP_O/d\Gamma$ unless we assume at a point in time one of the two scenarios mentioned above.

Substituting this relationship into Equation 2.1, we can express Equation 2.1 as:

$$\frac{dQ}{d\Gamma} = \left(-\frac{\partial S}{\partial P_O} \times \frac{P_O}{\Gamma}\left(\epsilon_{P_O,\Gamma} + A\right)\right) + \left(\frac{\partial S}{\partial P_{ES}} \times \frac{dP_{ES}}{d\Gamma}\right)$$

Again, for easier interpretation, we express the comparative static in elasticity form by multiplying by creative versions of one.

$$\frac{dQ}{d\Gamma} = -\left(\frac{\partial S}{\partial P_O} \times \frac{P_O}{Q}\right)\frac{Q}{\Gamma}\left(\epsilon_{P_O,\Gamma} + A\right) + \left(\frac{\partial S}{\partial P_{ES}} \times \frac{P_{ES}}{Q}\right)\frac{\partial P_{ES}}{\partial \Gamma}\frac{\Gamma}{P_{ES}}\frac{Q}{\Gamma}$$

$$\frac{dQ}{d\Gamma} = -\left(\epsilon_{S,P_o}\right)\frac{Q}{\Gamma}\left(\epsilon_{P_O,\Gamma} + A\right) + \left(\epsilon_{S,P_{ES}}\right)\left(\epsilon_{P_{ES},\Gamma}\right)\frac{Q}{\Gamma}$$

$$\frac{dQ}{d\Gamma} = \frac{Q}{\Gamma}\left(\epsilon_{S,P_o}\left(-\epsilon_{P_O,\Gamma} - A\right) + \epsilon_{S,P_{ES}}\epsilon_{P_{ES},\Gamma}\right) \tag{2.5}$$

As already established, ϵ_{S,P_o} is positive and $\epsilon_{S,P_{ES}}$, $\epsilon_{P_O,\Gamma}$ and $\epsilon_{P_{ES},\Gamma}$ are negative. Also, since supply and ethanol subsidy assume positive values, Q/Γ is positive. Our analysis, therefore, indicates that the effect of an ethanol subsidy on oil supply depends on the relative magnitudes of $\epsilon_{S,P_o}\left(-\epsilon_{P_O,\Gamma} - A\right)$ *and* $\epsilon_{S,P_{ES}} \times \epsilon_{P_{ES},\Gamma}$ in Equation 2.5. Since we know with certainty that the product of $\epsilon_{S,P_{ES}}$ and $\epsilon_{P_{ES},\Gamma}$ yields a positive outcome (the two terms are defined earlier as negative), the effect of an ethanol subsidy on oil supply will largely depends on the relative magnitudes of $\epsilon_{P_O,\Gamma}$ and A. If $\epsilon_{P_O,\Gamma}$ outweighs A, then $dQ/d\Gamma > 0$. This scenario implies that an ethanol subsidy will have a positive effect on the amount of oil extracted, thus evidence of a weak green paradox.

However, if this condition does not hold (thus, $\epsilon_{P_O,\Gamma} < A$), then an ethanol subsidy could result in two possible outcomes depending on the relative magnitudes of $\epsilon_{S,P_o}\left(-\epsilon_{P_O,\Gamma} - A\right)$ and $\epsilon_{S,P_{ES}}\epsilon_{P_{ES},\Gamma}$. Like before, a weak green paradox occurs if the negative effect ($\epsilon_{S,P_o}\left(-\epsilon_{P_O,\Gamma} - A\right)$) is outweighed by the positive effect ($\epsilon_{S,P_{ES}}\epsilon_{P_{ES},\Gamma}$), otherwise a weak green paradox does not occur.

A very relevant aspect of this analysis is understanding the factors that may influence the various elasticity values. In other words, the factors that may affect the magnitudes of the two effects causing the curves to be flat and/or steep relative to each other.

The degree of price elasticity of supply is explained among other factors by the spare production capacity, time horizon, and change in per-unit costs with increased production. For instance, when oil producers have enough spare production capacity to operate with, they can easily adjust to oil price hikes by expanding production. Similarly, a longer time horizon (long-run) or lower per-unit costs associated with expanding production will result in a relatively flatter supply curve, implying that a change in the price of oil will result in a more than proportionate change in the quantity of oil supply to the market. However, immediately after a price increase, producers can expand output using their current capacity making own price elasticity of supply inelastic. Similarly, when producers have little spare production capacity or when the per-unit costs associated with increased production is high, the less responsive they can be.

Additionally, the degree of elasticity between ethanol subsidy and the price of ethanol is determined by price controls. In some countries, energy prices are regulated by complex price control mechanisms (such as establishing price floors and ceilings) such that a sufficiently high incentive for ethanol producers (leading to lower production cost) may not translate to price reduction due to the institution of price controls. However, if there exists a flexible price control system that adequately adjusts prices to reflect production cost, then the degree of elasticity between an ethanol subsidy and the price of ethanol will be elastic. Also, when producers have enough market power to influence prices (such as an oligopoly market or the case where ethanol producers form cartels), an ethanol subsidy may not lead to the expected reduction in ethanol prices. Given such circumstances, the oligopoly producers or cartels can manipulate the market price and charge a relatively higher market price, hence an inelastic elasticity between an ethanol subsidy and ethanol price.

In the Brazilian context, Petrobras’ monopoly power can influence the degree of elasticity of supply. With 15 out of 17 refineries constituting over 90% of domestic refining capacity, all things being equal, Petrobras can respond quickly to oil price hikes by increasing production to meet the market demand. The large production capacity of Petrobras gives it the advantage of swiftly responding to changes in oil prices. Also, the per-unit cost associated with increased production would be lower for Petrobras relative to other private oil companies operating within the region considering the huge infrastructural investments Petrobras has made over the years and the governmental support it receives. These factors will cause the supply curve facing Petrobras to be relatively flat, implying that a more than proportionate quantity response will follow a change in oil price.

By implication, the full effects of an ethanol subsidy may not be observed as a result of Petrobras’ market power. As already mentioned, an ethanol subsidy is expected to influence not only the ethanol market but also the oil market. The mechanism that will result in behavioral change in the oil sector as a result of the implementation of an ethanol subsidy is the rent-seeking behavior of oil producers. Under the hotelling rule, oil producers respond to an ethanol subsidy when they anticipate a threat to their future profitability. However, Petrobras’ market power provides security towards its future profitability and as a result, it can deviate from hotelling rent-seeking behavior by not responding (or may respond marginally) to oil price hikes and curtail the full effect of an ethanol subsidy on the production of oil.

Chapter 3

Empirical Methodology

3.1 Data

To empirically analyze the effect of Brazilian biofuels policy of promoting the production of ethanol on the rate of extraction of oil and emissions, we employ annual data from Brazil over the period 1981 to 2018. The choice of duration is primarily due to the availability of data points for all variables used in this study. Energy data is obtained from the BP Statistical Review of World Energy and includes oil production and production of natural gas.[12] The outcome variable—oil production—is measured in MT and includes crude oil, shale oil, oil sands, condensates (both lease condensate and gas plant condensate), and NGLs (natural gas liquids—ethane, LPG and naphtha separated from the production of natural gas).

Natural gas excludes gas that has been flared or recycled. However, it includes natural gas produced for gas-to-liquids transformation and it is measured in millions of tonnes of oil equivalent. Data for ethanol production is collected from UNICA, and is measured in thousand cubic meters and includes hydrous and anhydrous ethanol. The Brent dated oil prices are measured in 2018 U.S dollars per barrel. Like the energy data, oil prices and emissions data are all collected from the BP Statistical Review of World Energy. All analyses are performed using Stata statistical software package version 14.0.

3.2 Description of Data

As shown in Table 3.1, the energy data for this study spans the period 1981 to 2018, generating 38 observations for each variable. Oil production accounts for the greatest share in the Brazilian energy mix with a mean of approximately 69 MT and a standard deviation of 40. The global annual crude oil price recorded a minimum of \$20 and a maximum of \$124 with an average of \$59 per barrel in nominal terms. The standard deviation value of 31 indicates the variability in

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[12] BP Statistical Review of World Energy 2019 provides historical data on world energy markets.

crude oil prices over the period. Ethanol production averaged 16,730 thousand cubic meters with a maximum production level of 33,103 thousand cubic meters which was recorded in 2018.

We further obtain annual time series data on national-level CO_2 emissions from BP Statistical Review of World Energy and International Energy Statistics from 1965 to 2018. The carbon emissions data reflect emissions from fuel only (thus, the consumption of oil, gas, and coal for combustion-related activities), and are based on "Default CO_2 Emissions Factors for Combustion" listed by the IPCC in its Guidelines for National Greenhouse Gas Inventories (2006). These guidelines do not allow for any carbon that is sequestered or carbon emitted from other sources, or for emissions of other GHGs. Emissions are measured in Million tonnes CO_2.

Table 3.1. Summary statistics

Variable	Obs.	Unit	Mean	Std. Dev.	Min	Max
Oil production	38	Mt	69	40	12	142
Ethanol production	38	M^3	16730	7639	4241	33103
Gas production	38	Mtoe	9	7	0.8	23
Crude oil prices	38	US$	59	31	20	124

3.3 The Vector Autoregressive Model (VAR)

The empirical study is based on the vector autoregressive model (VAR). VARs are considered to be a suitable class of models to model the dynamics of a set of endogenous time series variables. VARs have been used primarily in macroeconomics and are often suitable in situations when variables are stationary at levels or integrated of order one (I(1)) and are not cointegrated (Greene, 2005). The model estimates a system of equations (a seemingly unrelated regression model with identical regressors) that include lagged values of both the dependent and independent variables. When a VAR model is correctly specified (thus, the variables included are stationary) it produces the Best Linear Unbiased Estimators (BLUE).

VARs have proven to be more efficient in "analyzing and forecasting macroeconomic activity and tracing the effects of policy changes and external stimuli on the economy" than large-scale structural equation systems (Greene, 2005). Aside from forecasting, VARs are also employed in testing Granger causality and studying policy effects through impulse response functions. However, a major disadvantage of VARs is the high number of parameters.

Several tests are conducted to obtain the appropriate VAR structure for this study. First, the VAR model requires the determination of the optimal lag length. The Schwarz Bayesian information criterion (SBIC) indicates that the optimal lag length is one (Table 3.2). For completeness, we follow Grafton et al., (2014) and include longer lags of explanatory variables based on the Akaike Information (AIC), Hannan-Quinn information criteria (HQIC) and Likelihood-ratio (LR) information criteria. The primary reason for this test is to choose between models (i.e. models with longer or shorter lags of explanatory variables). However, all extra lags were found to be insignificant and as a result, the model with a one-year lag as predicted by SBIC is reported.

Table 3.2. Selection of optimal lag length

	Information Criteria					
Lag	Df	P	LR	AIC	HQIC	SBIC
0				38.785	38.908	39.144
1	16	0.000	168.13	34.781	35.149	35.859*
2	16	0.000	50.222	34.245	34.858	36.041
3	16	0.000	55.324	33.559	34.417	36.073
4	16	0.000	44.393*	33.195*	34.297*	36.427

An asterisk (*) implies the optimal lag length chosen by the information criterion

To decide whether to include a deterministic trend or not in the model, we graph both the level and differenced series and the outcome is presented in Figure 3.1.

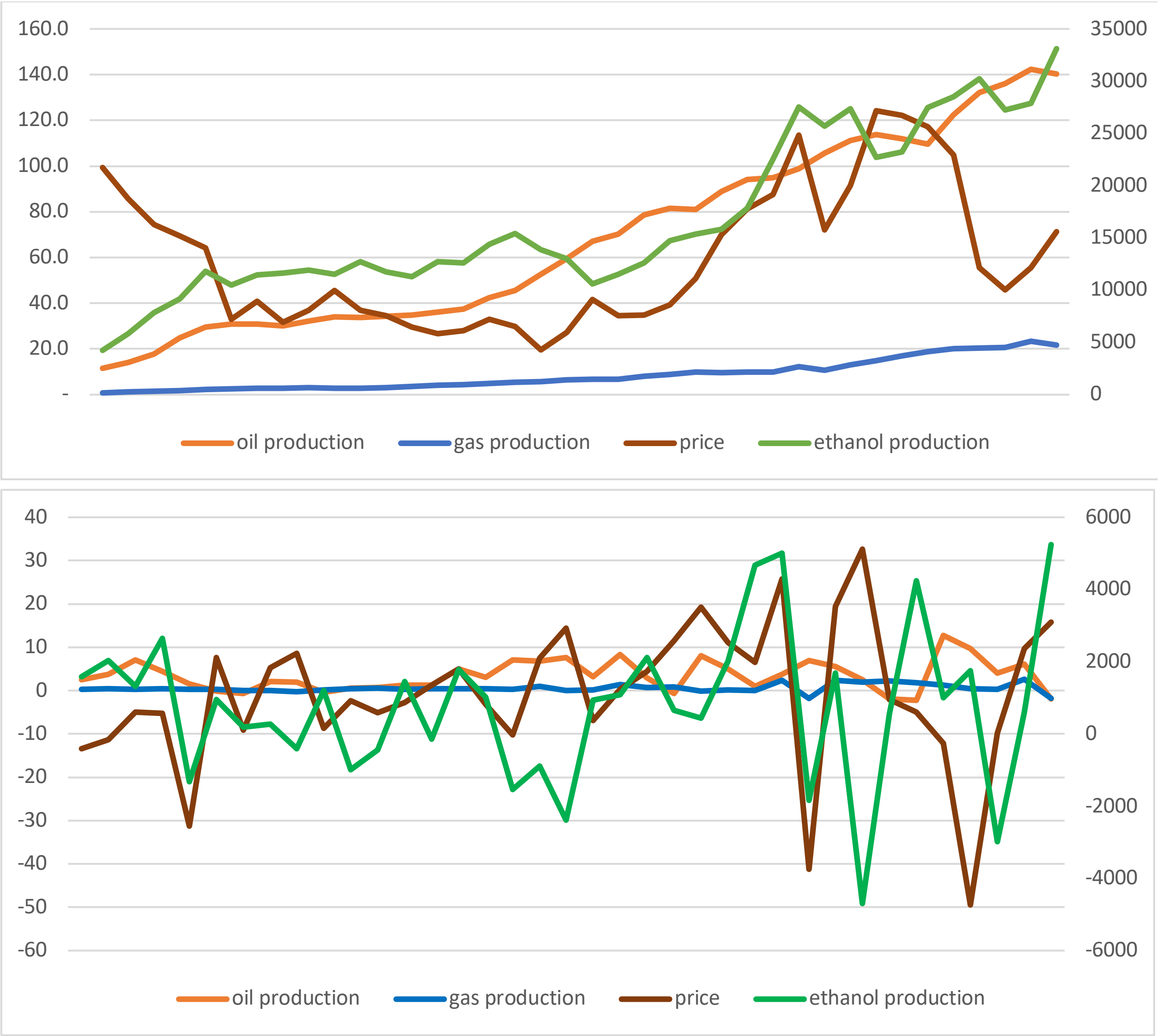

Figure 3.1. Time series graph

Note: The upper panel represents the graph for the level variables and the lower panel is the graph for the differenced series.

The visual inspection of the time series graph indicates that all variables (at levels) exhibit an upward trend. However, the differenced data takes away the trend in the series. Based on these outcomes, a VAR model without a deterministic trend is specified (Equation 3.1) to (Equation 3.4) and estimated (Table 4.1).

Before running a causality test in time series analysis, it is germane to estimate the order of integration and stationarity conditions of all variables. A stationary time series is one whose mean, variance and covariance do not vary over time. If a series is non-stationary (i.e. the presence of unit root), the regression outcome will most likely be spurious. For this purpose, we perform the test for stationarity using the conventional ADF test, the Dickey-Fuller generalized least square (DF-GLS) proposed by Elliott et al. (1996) and the Phillips-Perron test following Phillips and Perron (1988). The different approaches are adopted since there are no uniformly most powerful stationarity tests. Although the ADF test has been widely used in most studies, Elliott et al. (1996) showed that the test has low power compared to the DF-GLS. For completeness, we use three common unit root test approaches. The maximum lag selected by the Schwert criterion in the DF-GLS test is 9 and results for the three different tests are presented in Table 3.3 below.

Table 3.3. ADF, DF-GLS, and Phillips-Perron tests for unit root

Variables	ADF test			DF-GLS test			PP test	
	SBIC lag	t-Stat	5% CV	SC lag	t-Stat	5% CV	z(t)	5% CV
Panel A: Variables at levels (Including Trend)								
Oil production	1	-1.91	-3.556	1	-1.52	-3.190	-1.58	-3.552
Ethanol production	1	-1.94	-3.556	1	-1.99	-3.190	-1.90	-3.552
Gas production	1	-0.67	-3.556	1	-0.52	-3.190	-1.23	-3.552
Crude oil prices	1	-2.51	-3.556	1	-1.61	-3.190	-2.53	-3.552
Panel B: Variables in the first difference (No Trend)								
ΔOil production	0	-4.33	-3.675	1	-3.92	-3.190	-4.19	-3.556
ΔEthanol production	0	-5.20	-3.675	1	-3.60	-3.190	-5.04	-3.556
ΔGas production	0	-6.63	-3.675	1	-3.04	-3.190[a]	-7.51	-3.556
ΔCrude oil prices	0	-5.42	-3.675	1	-3.63	-3.190	-5.40	-3.556

[a] Gas production becomes stationary at a 10% critical level (-2.890) as such this value is interpreted to be stationary at first difference.

The outcomes of the unit root tests are similar across the different approaches. In all tests, each variable is non-stationary at levels, implying the presence of a unit root. The first difference of the variables leads to the rejection of the null hypothesis of a unit root at the 5% significance level except for natural gas where the null is rejected at a 10% level with the DF-GLS test. Based on these results, we conclude that all variables are integrated of order one.

In this specific event that all variables are I(1), time series analysis requires the test for the presence of cointegrating relationships among variables. This test informs the existence of a long-run cointegrating relationship. It is significant because it allows for the testing of plausible economic relationships among non-stationary time series variables, under the assumption of long-run equilibrium. We employ the Johansen approach in conducting the cointegration test. Since most of the series have been established to have a trending behavior (see Figure 3.1), a linear trend term is included in the cointegration test specification. The lag order of the VAR which is behind the cointegration test analysis is based on the order chosen according to the SBIC. We select the lag order based on SBIC because of problems linked with explosive impulse response functions associated with longer orders (Cologni and Manera, 2008). Again, a priori, we do not expect a significant relationship between energy variables that goes "too far" back (confirmed in the model selection test).

Table 3.4. Johansen cointegration test

H0:	H1:	Trace Test			λ −max Test		
Rank $= r$	Rank $> r$	Trace Statistic	5% Critical Value	Eigenvalue	Max Statistics	5% Critical Value	Eigenvalue
0	0	35.091*	54.64	–	19.0377	30.33	–
1	1	16.054	34.55	0.40222	9.5648	23.78	0.40222
2	2	6.489	18.17	0.22780	3.9113	16.87	0.22780
3	3	2.577	3.74	0.10032	2.5774	3.74	0.10032
4	4			0.06729			0.06729

An asterisk (*) implies the significance of the test statistics at 5% significance level.

Table 3.4 provides evidence of no long-run relationship among the variables. We, therefore, impose no cointegrating restriction and estimate a VAR with the variables entering the first difference. The VAR models specified in equations 3.1 to 3.4 include the following four variables: oil production, ethanol production, gas production, and oil prices. For equation 3.1, we present results for two models: a model that includes a constant and another that suppresses the constant term.[13] The model with a suppressed constant—thus, Regression Through the Origin (RTO)—is included to directly predict changes in oil as a linear function of changes in the other regressors, without reference to the current levels of the variables. Thus, by this, we assume that

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[13] For simplicity we only specify the equations with constants.

oil production will remain unchanged, on average, if the price of oil and productivity level of the other forms of energy are unchanged. The estimation results are presented in Table 4.1 in Chapter 4.

$$\Delta Oil_{\ t} = \alpha_1 + \sum_{i=1}^{k} \beta_{1i} \Delta Oil_{t-1} + \sum_{j=1}^{k} \theta_{1j} \Delta Ethanol_{t-1} + \sum_{m=1}^{k} \varphi_{1m} \Delta Gas_{t-1} + \sum_{n=1}^{k} \delta_{1n} \Delta Oil\_Prices_{t-1} + e_{1t} \tag{3.1}$$

$$\Delta Ethanol_{\ t} = \alpha_2 + \sum_{i=1}^{k} \beta_{2i} \Delta Oil_{t-1} + \sum_{j=1}^{k} \theta_{2j} \Delta Ethanol_{t-1} + \sum_{m=1}^{k} \varphi_{2m} \Delta Gas_{t-1} + \sum_{n=1}^{k} \delta_{2n} \Delta Oil\_Prices_{t-1} + e_{2t} \tag{3.2}$$

$$\Delta Gas_{\ t} = \alpha_3 + \sum_{i=1}^{k} \beta_{3i} \Delta Oil_{t-1} + \sum_{j=1}^{k} \theta_{3j} \Delta Ethanol_{t-1} + \sum_{m=1}^{k} \varphi_{3m} \Delta Gas_{t-1} + \sum_{n=1}^{k} \delta_{3n} \Delta Oil\_Prices_{t-1} + e_{3t} \tag{3.3}$$

$$\Delta Oil\_Prices_{\ t} = \alpha_4 + \sum_{i=1}^{k} \beta_{4i} \Delta Oil_{t-1} + \sum_{j=1}^{k} \theta_{4j} \Delta Ethanol_{t-1} + \sum_{m=1}^{k} \varphi_{4m} \Delta Gas_{t-1} + \sum_{n=1}^{k} \delta_{4n} \Delta Oil\_Prices_{t-1} + e_{4t} \tag{3.4}$$

All variables are as previously defined in the data section. The parameters α_1 to α_4 and e_{1t} to e_{4t} represent constants and residuals in each equation. The optimal lag length is represented as k. β, θ, φ and δ are the short-run dynamic coefficients to be estimated and Δ represents the first difference operator. We emphasize that because one of the primary objectives of this study is to ascertain the influence of ethanol production on the rate of oil extraction, Equation 3.1 is the primary focus among the systems of equations, and as such results are only explained for the equation of interest. However, the results for Equation 3.2 to Equation 3.4 are provided in Table A.1 in the Appendix.

To further understand how oil production responds to exogenous shocks, we conduct an impulse response analysis. An impulse response captures the reaction of a dynamic system to an exogenous change. The response function provides the time profile of the effect of an external change that occurs at a given time on the expected values of variables in a dynamic system (Koop, Pesaran, and Potter, 1996). We specifically focus on the response of oil production to a one standard deviation shock in ethanol production. The results are presented in Figure 4.1 in the succeeding chapter.

To achieve the second objective of this study—whether or not there is evidence for a strong green paradox—we follow Grafton et al. (2014) and evaluate the net effect of a one-for-one substitution of ethanol for oil on CO_2. We conduct our evaluation based on the proportional increase in oil production resulting from a one percent rise in ethanol production given the 2018 production values for oil and ethanol. We specify based on our results from Table 4.1 that a one percent rise in Brazil's change in ethanol production in period T will result in a 1.5 and 4.9[14] percentage increase in the change in oil production in the short-run and long-run, respectively[15]. To standardize the units of measurement of the energy and emission variables, we use the approximate conversion factors adopted from the 2019 report of BP Statistical Review of World Energy. The conversion factors employed are: 1 metric tonne equals 7.33 barrels; 1 meter cube equals 6.3 barrels of oil; 1 tonne of CO_2 equals 1.10231 US ton of CO_2. Table 4.2 presents the results for the effect of Brazil's ethanol production on CO_2 emissions.

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[14] The computation for the short-run and long-run elasticity values can be found in Equation A.5 and Equation A.7 in the Appendix.

[15] We define the short-run as the time period over which oil producers cannot easily switch from the production of oil to the production of ethanol. However, in the long-run—thus, a period of time fairly long for oil producers to channel their resource into the production of oil—the marginal cost of producing oil is higher than that of ethanol.

Chapter 4

Results and Discussion

The green paradox theory predicts that renewable energy policies aimed at encouraging the substitution away from fossil fuels may increase the incentive for fossil-fuel producers to increase their current rate of extraction, accentuating climate change damages. Renewable energy policies such as biofuel subsidies may pose a threat to the future profitability of fossil-fuel owners resulting in a behavioral change (thus, extracting more now rather than later). The effects of the behavioral change of fossil-fuel owners can be observed through an increase in the rate of fossil extraction and consequently an increase in carbon emissions. The increase in the rate of fossil extraction as a result of the direct effect of a renewable energy policy is classified as a weak green paradox in this study. A strong green paradox occurs when the overall CO_2 emissions in Brazil increase due to renewable energy policy.

In this study, we examine the effectiveness of Brazil's renewable energy policy by observing changes in the level of production. Since one of the principal objectives of renewable energy policies such as biofuel subsidies, wind, and solar energy is to provide energy with fewer emissions, it is important to examine the effectiveness of such policies on production. For instance, Grafton et al. (2014) found that the biofuel subsidy program of the United States government played a very significant role in the expansion of biofuel production in the US. They observed a correlation of 0.9978 between US biofuel subsidies and biofuel production and further used biofuel production instead of biofuel subsidies as their explanatory variable due to data challenges. We follow Grafton et al. (2014) and employ ethanol production as a proxy for renewable energy policy in this study.

Since Brazil has encouraged not only the production but also the consumption of ethanol through several measures prescribed by the ProAlcool program, the effect of such a program can be observed in the level of production. As already recounted in the section titled Brazil's Ethanol Experience, some of the measures adopted by Brazil to promote ethanol production range from the use of subsidies and blending mandates to general industry support in the form of public research investment.

Although we do not restrict our attention to a single policy measure (such as an ethanol subsidy or a tax incentive) and trace out its effect on the rate of oil extraction, we consider the effect of increased ethanol production on the rate of extraction. The level of ethanol production more generally captures the various policy measures aimed at promoting its production. For instance, large-scale financial incentives to ethanol producers are expected to have an implication on the level of ethanol production, providing a direct relationship between such an incentive and production. Again, a very good reference point is the work of Grafton et al. (2014).

Based on this premise, the main testable hypothesis that satisfies the first objective of this study is that oil producers in Brazil respond to an expansion in ethanol production by increasing the rate of oil extraction. Evidence of such a relationship would provide support for a weak green paradox.

The VAR results from the first equation of our VAR model (Equation 3.1) testing for the existence of a weak green paradox is presented in Table 4.1. We examine a model that has change in oil production in the current period as the dependent variable regressed on a one-period lagged change in oil and ethanol productions, one-period lagged change in natural gas, and one-period lagged change in the price of oil. We present results for two models: models with and without a constant.

The results from the regressions reveal a positive relationship between the one-period lagged change in oil production and the current period's change in oil production. An MT increase in the last period's change in oil production will lead to a 0.268 MT (Column 1) and 0.522 MT (Column 2) rise in the current period's change in oil production. This is significant at the ten percent significance level and implies that future oil supply decisions are influenced by current production.

The estimated coefficient of ethanol production is positive and statistically significant at the ten-percent significance level (Column 1). The results indicate that a change in Brazil's ethanol production from one period ago influences the change in oil production in the current period. Specifically, a cubic meter (m^3) rise in the change in Brazil's ethanol production in the previous period would result in a 0.53 m^3 (0.000530 MT) to 0.64 m^3 (0.000639 MT) increase in the change in oil production in the current period. The computed short-run and long-run elasticities of the change in oil production with respect to a change in ethanol production are 1.5 and 4.9, respectively. These elasticity values imply that a 1 percent increase in the change in ethanol production would increase the change in oil production by 1.5 percent in the short-run and 4.9

percent in the long-run. The results provide evidence for the existence of a weak green paradox for Brazil, although at a low level of significance. Thus, an expansion in ethanol production is associated with greater oil production over the time frame we study.

It is possible, however, that the seemingly small coefficient for Brazil's oil production with respect to ethanol production could be as a result of the strong involvement of the state in the oil sector. Brazil is home to 17 refineries, out of which Petrobras—the national oil company operates 15. Brazil's downstream oil industry is largely controlled by Petrobras, whose facilities represent more than 90% of domestic refining capacity. However, Brazil opened the oil sector to other companies after amending the 1995 constitution and ended the monopoly reign of Petrobras. Also, the introduction of Concession Bidding Rounds and the amendment of the Production Sharing Law that empowered Petrobras to solely operate the Pre-Salt area opened the possibility for other companies to operate in the Pre-Salt.[16] The constitutional amendments and Petrobras' decision to encourage the divestment of both upstream and downstream assets have "created unprecedented opportunities for other companies" (Oddone 2016).[17]

The de-facto monopoly power of Petrobras and largely the state in the sector could hamper the full effect of an upsurge in ethanol production on the rate of oil extraction. The state (Petrobras) can afford to deviate from rent-seeking behavior and provide minimal to no quantity response in the face of increasing ethanol production. Nonetheless, there could be a quantity response from other private companies whose extraction decisions are motivated by profit. The evidence from Table 4.1 shows that owners follow the Hotelling's rule, thus, their decisions are based on rent. This implies that owners of oil resources (perhaps the private operators) would extract rather than keep the resource in the ground when they anticipate a future drop in profits as a result of greater ethanol production.

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[16] The developments in this paragraph are covered extensively in the Oil and Gas Year Brazil 2019 published in collaboration with the Rio de Janeiro State Federation of Industries (Firjan) and Brazil's National Agency of Petroleum, Natural Gas and Biofuels (ANP); Petrobras "Annual Report 2018".

[17] For example, Equinor, Shell and ExxonMobil have all committed to increasing their investment in Exploration and Production in Brazil (EPE, 2019).

Table 4.1. Dynamic linear regression model of oil production in Brazil

Variables	Δ(Oil Production)$_t$	
	(1) Model with a constant	(2) Model without a constant
Δ(Oil production)$_{t-1}$	0.268*	0.522***
	(0.161)	(0.136)
Δ(Ethanol production)$_{t-1}$	0.000530*	0.000639**
	(0.000285)	(0.000306)
Δ(Gas production)$_{t-1}$	-0.255	0.542
	(0.723)	(0.705)
Δ(Crude oil prices)$_{t-1}$	-0.0264	-0.0432
	(0.0383)	(0.0409)
Constant	2.314**	
	(0.919)	
Observations	36	36
Parms	5	5
RMSE	3.4885	3.724
R-Square	0.1612	0.5029
P>chi2	0.1403	0.0000

Standard errors in parentheses. Significance denoted by: *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Our post estimation Lagrange-multiplier (LM) test for residual autocorrelation reveals the presence of no autocorrelation at the optimal lag. No evidence of serially correlated residuals was found for the model after testing for up to AR(4) in the LM test in Table A.2. The Eigenvalue stability condition suggests all eigenvalues lie inside the unit circle implying that the model satisfies the stability condition (Figure A.1). The Jarque-Bera test (Table A.3) for normally distributed disturbances shows that the equation of interest—the equation for oil production, Equation 3.1, is normal. These test results indicate that the relationship established between the regressors and oil production is consistent, asymptotically efficient, and dynamically stable and that OLS estimation provides the best possible estimates (Greene 2005).

The responses of oil production to positive shocks (or innovations) to energy and price variables are presented in Figure 4.1. The impulse responses are constructed under the assumption of a one standard deviation shock from regressors. In each graph, we present the 95% confidence interval as the graph confidence bands. We find persistence in the shocks whether we estimate a model with a suppressed constant or not, therefore, we report shocks for only the model with a constant.

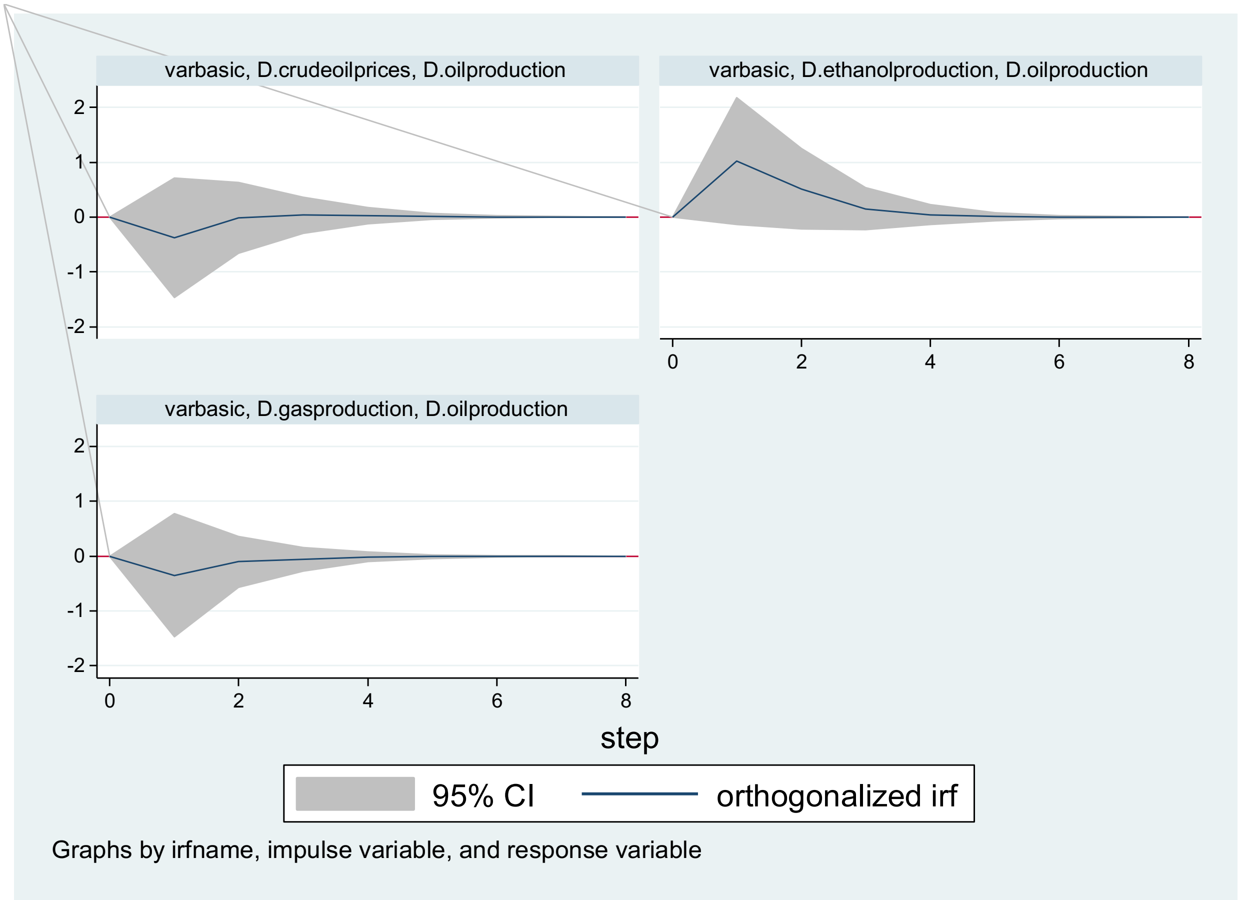

Figure 4.1. **Impulse responses of oil to positive shocks from regressors**

Results from the impulse response graph provides no evidence to support the claim that shocks (one standard deviation) from oil prices, ethanol production, and gas production lead to a statistically significant response from oil production. Impulses from oil prices, ethanol production, and gas production do not result in a statistically significant change in oil production across the 8-period duration at the 95% confidence interval.

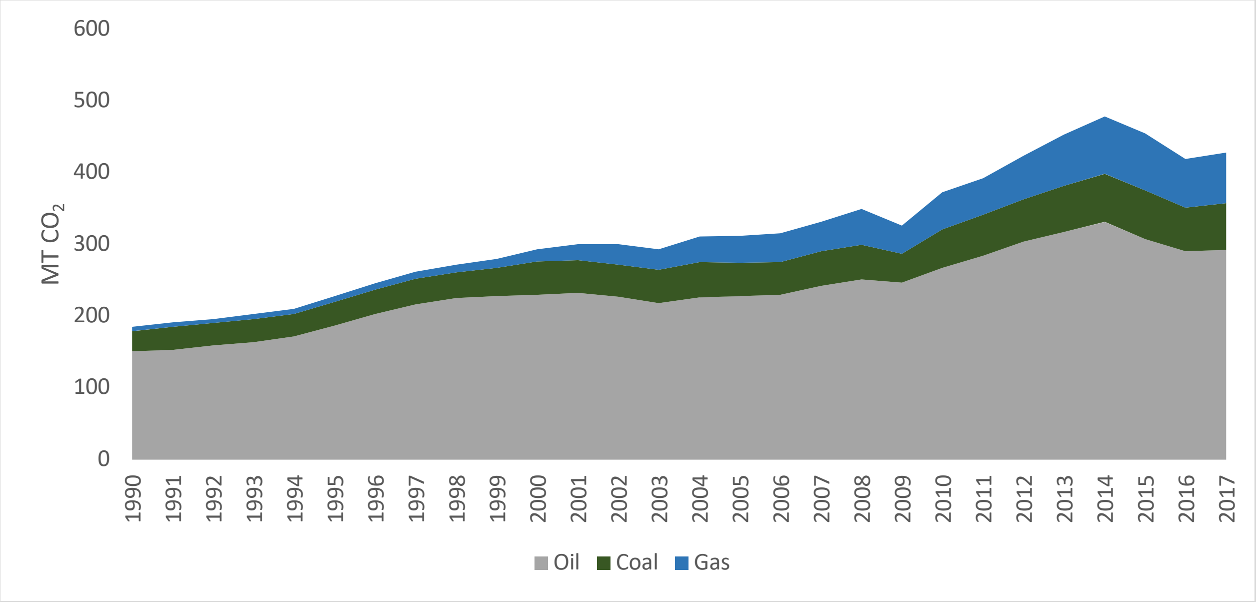

Figure 4.2. CO_2 Emissions by energy source (MT CO_2)

From 1990, Brazil's carbon emissions have exhibited an upward trend with the year 2014 recording the highest CO_2 emission of approximately 505 MT (Figure A.2). In terms of emissions by energy sources, the production of oil accounts for the largest share of CO_2 emissions among the three energy sources. Until the year 2008, coal production resulted in much greater carbon emissions than the production of gas. However, in 2008 as well as the year 2012 and beyond, the production of gas has accounted for higher carbon emissions than coal (Figure 4.2).

The Brazilian transport sector has been a dominant force in carbon emissions over the years. Over the period 1990-2017, the sector has accounted for the greatest share of carbon emissions. Until the year 2012, electricity and heat production resulted in only a small proportion of CO_2 emissions. However, beyond this period, the amount of carbon emissions by the sector is nearing that produced by the industry sector. The least amount of carbon emissions is produced by the Commercial and Public services sector (Figure 4.3).

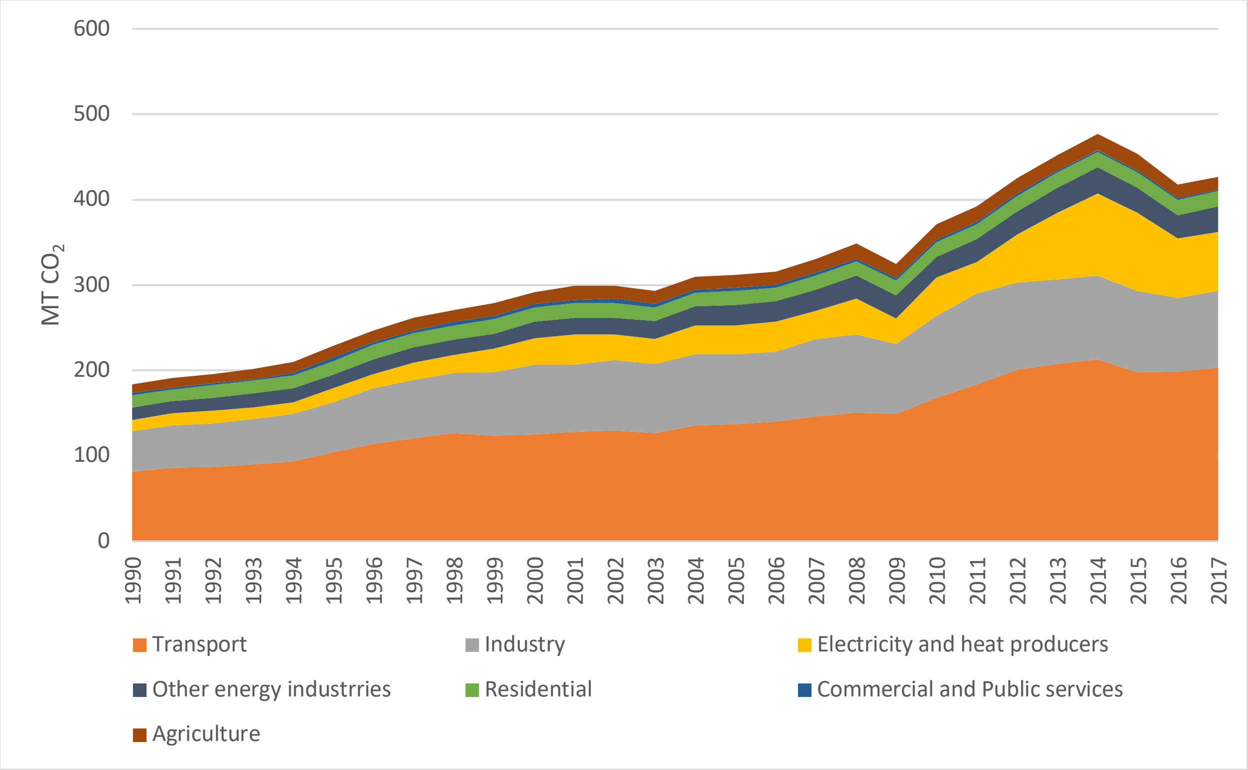

Figure 4.3. CO_2 Emissions by sector (MT CO_2)

For a strong green paradox to exist, the net CO_2 emissions have to be positive. Thus, the amount of CO_2 emitted from fossil fuels must outweigh the corresponding reduction in CO_2 from ethanol due to the substitution of ethanol for fossil fuels (specifically oil). To provide evidence for the strong green paradox, we specify that crude oil emits 0.43 metric tons CO_2/barrel (EPA 2019). To specify all units related to CO_2 emissions in one thousand barrels, the 0.43 metric tons CO_2/barrel will imply that every one thousand barrels of oil produced emit an equivalent of 430 metric tons of CO_2.

While a thousand barrel of crude oil emits 430 metric tons of CO_2, we evaluate the proportional CO_2 emissions reduction from ethanol, due to a one-for-one substitution of ethanol for oil by a scale factor X, given the computed short and long-run elasticities. We define X as the proportion of CO_2 that is not released into the atmosphere due to a one-for-one replacement of oil with ethanol fuel. Specifically, X captures the proportion of CO_2 emissions reduction from ethanol, on a one-for-one substitution for oil, resulting from a one percent increase in the production of ethanol from a given baseline level – 2018 production. We specify different levels of the proportional CO_2 reduction factor (X) ranging from 0.1 to 3.

As shown in Table 4.2 below, a strong green paradox exists if the CO_2 emission reduction resulting from a one-for-one substitution of ethanol for fossil fuel is less than 0.73 in the short run and 2.44 in the long run. This implies that ethanol production in Brazil results in a net increase in CO_2 emissions if the emission reduction from ethanol that is substituted for oil is less than 73 percent in the short run and 244 percent in the long run. However, evidence for a strong green paradox in Brazil erodes whenever emission reduction from ethanol based on a one-for-one substitution of ethanol for oil is greater than 0.73 in the short run and 2.44 in the long run. These results provide evidence for a strong green paradox in the Brazilian context.

The highest net CO_2 emission occurs when the CO_2 emission reduction from substituting ethanol for oil is 10 percent. At this level, the corresponding CO_2 emission is 569,210 MT in the short run and 2,095,970 MT in the long run. These values respectively correspond to 0.117 percent and 0.430 percent of total Brazil's CO_2 emissions from energy consumption. The proportion of Brazil's emissions to total emissions from energy consumption reduces to 0.098 percent and 0.412 percent in the short and long runs respectively when the per-unit CO_2 emissions reduction from replacing oil with ethanol increases to 20 percent.

Table 4.2. The effect of ethanol production on Brazil's CO_2 emissions

			Change in CO_2 emission due to a 1% increase in biofuels production (metric tons CO_2)								
1% rise in ethanol production		Increase in oil from a 1% rise in ethanol production	0.1	0.2	0.50	0.60	0.73	0.9	2	2.73	3
SR	2085	1532	569210	479534	210506	120829	0	-148199	-1134635	-1527252	-2031395
LR	2085	5083	2095970	2006315	1737350	1647695	1526894	1378730	392525	0	-504025
			Change in CO_2 emission relative to total Brazil CO_2 emissions from energy use (%)								
		SR	0.117	0.098	0.043	0.025	0	-0.030	-0.233	-0.314	-0.417
		LR	0.430	0.412	0.357	0.338	0.314	0.283	0.081	0.000	-0.103

A positive number in terms of the change in CO_2 emission is consistent with the hypothesis of a Strong Green Paradox while a negative number is not.

There are several caveats with the analysis. First of all, the changes in CO_2 emissions are highly sensitive to the energy data (i.e. ethanol and oil production in 2018), computed short and long-run elasticity values, and the approximate conversion rates. Any significant change in any of these factors will alter the outcome in Table 4.2. Also, our computations for the change in CO_2 emissions relative to total CO_2 emissions from energy use and changes in CO_2 emissions are based on 2018 emissions and energy data. This implies that our assessment is explicitly limited to this baseline year, and results do not reflect overall CO_2 emissions over the study period (thus, 1981 to 2018). We, therefore, advise that, since our computations do not use high-frequency data to evaluate the existence of a strong green paradox or otherwise, these results must be interpreted with caution. These notwithstanding, our conservative results provide evidence for a strong green paradox in the Brazilian context.

It is possible that other factors aside the green paradox could potentially lead to a similar outcome as obtained in this study. Factors such as Petrobras' internal production targets and the discovery of new oil fields among others, could result in greater extraction independent of an ethanol expansion. Even if this is true, we argue that the dominant factor driving our results is the green paradox based on two reasons. First, the Brazilian government's policy intervention designed to decrease the cost of ethanol by investing in and subsidizing the domestic ethanol industry has increased ethanol production resulting in the observed supply response from oil producers. Even if we suspect that Petrobras' production target and the discovery of oil fields have potentially resulted in increased production of oil, these effects are only minimal and do not explain much of the observed supply response relative to the reaction generated by greater ethanol production.

Secondly, the Brazilian fuel market's uniqueness provides reasonable evidence to support the proposition that our results are driven by the green paradox and not other alternative forces. Brazil is the only country in the world with dedicated ethanol pumps at various fuel stations providing the opportunity to easily assess ethanol fuel. The ability of consumers to easily substitute between ethanol and oil at minimal or almost zero search and transaction costs generates competing use for ethanol and oil. Even in the phase of increased production targets and/or discoveries, the observed competition between the two alternative fuels would trigger a much greater supply response from oil producers. Thus, with the ease of accessing ethanol fuel, the supply response from oil suppliers due to competition from ethanol usage will be greater than the supply response generated by, say new discoveries. It must be pointed out that discovery does not imply extraction. Therefore, we argue that a possible way of inducing extraction even on newly discovered wells is through competition generated from the ethanol sector. Since competition from the ethanol sector threatens the future profits of oil suppliers, the natural response is to increase current extraction as captured in our results. For these reasons, we can ascribe the observed supply response from oil owners to the green paradox (i.e., increased extraction due to expansion in ethanol production) rather than other alternative factors.

Chapter 5

Conclusion and Policy Recommendations

After Sinn (2008) ignited the debate on the green paradox, several studies have examined when a green paradox may occur under different policy scenarios. A very comprehensive analysis concerning the theoretical mechanisms that could result in a green paradox is provided by van der Werf and Di Maria (2012). They analyze conditions under which well-intended emission correction policies may lead to undesirable unintended consequences—a green paradox. Generally, a green paradox may emerge under four possible conditions: (a) Significant time lags between policy announcement and implementation (Ssmulders, Tsur, and Zemel 2012; Di Maria, Smulders, and Van der Werf, 2012); (b) Unreasonable pricing of carbon (Hoel, 2010); (c) Policies that favor alternative energy to fossil fuels (Grafton et al., 2014; van der Ploeg and Withagen, 2012); and (d) Unilateral climate policies (Sen, 2016).

In this study, we empirically investigate the third condition by evaluating whether Brazil's biofuel policy aimed at reducing domestic demand for fossil fuels whiles promoting the use of ethanol and at the same time taking advantage of its surplus sugarcane supply go against the spirit of the proposed regulation. In particular, we study whether Brazil's ethanol expansion has resulted in greater oil extraction—a weak green paradox, and/or let to an increase in net carbon emissions—a strong green paradox.

The results indicate that oil extraction has increased as a result of Brazil promoting greater ethanol production. Specifically, the change in oil production in the following period increases by 0.53 m^3 (0.000530 MT) to 0.64 m^3 (0.000639 MT) following a cubic meter rise in the change in ethanol production in the preceding year, providing evidence for the weak green paradox. The computation of the short and long-run elasticities reveal that a one percent rise in the change in ethanol production would increase the change in oil production by 1.5 percent in the short-run and 4.9 percent in the long-run. The impulse response analysis, however, provided no support for the claim that an innovation that triggers an expansion in ethanol production produces a response from oil producers.

Whether the rise in oil production following an expansion in ethanol production has led to an overall rise in CO_2 emissions required that we analyze net CO_2 emissions based on a one-for-one substitution of ethanol for oil. Our analysis indicates that net CO_2 emission in Brazil is positive if the CO_2 emission reduction resulting from a one-for-one substitution of ethanol for fossil fuel is less than 73 percent in the short run and 244 percent in the long run, thus, evidence for a strong green paradox. This outcome suggests that Brazil's ethanol policy aimed at reducing domestic demand for fossil fuels whiles promoting the use of ethanol and at the same time taking advantage of its surplus sugarcane supply could have produced effects that go against the spirit of the proposed regulation.

Although these findings provide evidence for the green paradox in the Brazilian context, our results are subject to caveats that require that our outcome must be interpreted with caution. The unavailability of high-frequency state-level production data to test particularly the strong green paradox presents some data limitations in our studies. Also, our assessment of the strong green paradox is explicitly limited to a specific baseline year and results do not reflect overall CO_2 emissions over the study period. Nevertheless, our findings have provided some empirical evidence that indicates that Brazil's ethanol policy could, paradoxically, have caused overall carbon emissions to increase.

Our results support the view that a single emission correction policy may not be adequate to tackle the green paradox. Perhaps, policies designed to address the world's greatest public good problem should address both demand and supply simultaneously. Tackling the green paradox only from the supply or demand side of the market may not yield the desired outcome of reducing net CO_2 emissions. At the very least, Brazil and other policymakers must carefully evaluate a one-sided policy to ascertain whether or not their implementations have the potential of increasing fossil extraction and ultimately increasing CO_2 emissions whether in the present or near future. Also, the Brazilian government, as well as other policymakers, should consider the implementation of complementary policies in competing energy industries such that the unintended undesirable penalties of implementing lone policies are eliminated, or at worse minimized. Lastly, when a single emission correction policy such as an ethanol subsidy is inevitably relevant, policymakers should cautiously consider to what extent the ethanol subsidy should increase. This is relevant because the degree of such an incentive does not only influence the ethanol industry but also plays a crucial role in the extraction behavior of oil producers.

This study provides new insights into the Brazilian energy sector by shedding light on one of the most important challenges facing the world today, climate change. However, a further step would be to consider the effects of multiple emission correction policies, such as the concurrent implementation of a carbon tax and an ethanol subsidy on emissions by using long data which admittedly are difficult to obtain. Additionally, further research is needed to test the green paradox in a resource market with imperfect competition. In the presence of market power, a renewable incentive may not yield the desired outcome since dominant fossil fuel producers could maintain and reinforce their monopoly power by undercutting oil prices to keep renewable producers out of the market. This is an area that future research could focus to provide sound micro-evidence of the effect of an incentive for renewable energy on emissions amid imperfect competition.

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APPENDIX A

Table A.1. Regression estimates for Equation 3.2 to Equations 3.5.

VARIABLES	Δ(Ethanol Production)$_t$	Δ(Gas Production)$_t$	Δ(Crude oil Prices)$_t$
Δ(Oil production)$_{t-1}$	-38.19	-0.0405	-0.777
	(103.1)	(0.0441)	(0.759)
Δ(Ethanol production)$_{t-1}$	0.0646	-0.000133*	-0.00185
	(0.183)	(7.83e-05)	(0.00135)
Δ(Gas production)$_{t-1}$	-289.9	-0.0739	-3.341
	(463.9)	(0.198)	(3.415)
Δ(Crude oil prices)$_{t-1}$	13.69	-0.00948	0.138
	(24.59)	(0.0105)	(0.181)
Constant	1,053*	0.839***	5.897
	(589.6)	(0.252)	(4.340)
Observation	36	36	36

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Computation of short-run and long-run elasticities

The regression equation is specified as:

$$\Delta Oil_t = \alpha_1 + \beta_{1i}\Delta Oil_{t-1} + \theta_{1j}\Delta Ethanol_{t-1} + \varphi_{1m}\Delta Gas_{t-1} + \delta_{1n}\Delta Price_{t-1} \quad \text{(A. 1)}$$

Using only significant variables from the regression results from Table 4.1, Equation A. 1 reduces to:

$$\Delta Oil_t = \alpha_1 + \beta_{1i}\Delta Oil_{t-1} + \theta_{1j}\Delta Ethanol_{t-1} \quad \text{(A. 2)}$$

The formula for the calculation of the elasticity values is expressed as:

$$\in_s = \frac{\Delta Oil}{\Delta E} \times \frac{\bar{E}}{\overline{\overline{Oil}}} = \left[\frac{\alpha_1}{\Delta E_{t-1}} + \beta_{1i}\frac{\Delta Oil_{t-1}}{\Delta E_{t-1}} + \theta_{1j}\frac{\Delta E_{t-1}}{\Delta E_{t-1}}\right]\left[\frac{\bar{E}}{\overline{\overline{Oil}}}\right] \quad \text{(A. 2)}$$

$$\in_s = \left[\frac{\alpha_1}{\Delta E_{t-1}} + \beta_{1i}\frac{\Delta Oil_{t-1}}{\Delta E_{t-1}} + \theta_{1j}\right]\left[\frac{\bar{E}}{\overline{\overline{Oil}}}\right] \quad \text{(A. 3)}$$

where E is ethanol production.

Substituting the estimates from Table 4.1 into Equation A.3 yields:

$$\in_s = \left[\frac{2.314}{604.264} + 0.268\left[\frac{6.117}{604.264}\right] + 0.000530\right]\left[\frac{29405.35}{139.6}\right] \tag{A. 4}$$

$$\in_S = 1.489473 \tag{A. 5}$$

Thus, the short-run elasticity of change in oil production in period T with respect to a change in ethanol production in period $T - 1$ is 1.489473.

The long-run elasticity of change in oil production in period T with respect to a change in ethanol production in period $T - 1$ ($\in *_s$) is computed using the formula:

$$\in *_s = \frac{\in_S}{1 - \beta_{1i} **}$$

But, $$\beta_{1i} ** = \left[\frac{\alpha_1}{\Delta Oil_{t-1}} + \beta_{1i} + \theta_{1j}\frac{\Delta E_{t-1}}{\Delta Oil_{t-1}}\right]\left[\frac{\overline{Oil_{t-1}}}{\overline{\Delta Oil_t}}\right]$$

$$\beta_{1i} = \left[\frac{2.314}{6.117} + 0.268 + 0.00053\left[\frac{604.264}{6.117}\right]\right]\left[\frac{139.2583}{139.6}\right]$$

$$\beta_{1i} = 0.698537$$

Therefore,

$$\in *_s = \frac{1.489473}{(1 - 0.698537)} \tag{A. 6}$$

$$\in *_s = 4.940811 \tag{A. 7}$$

Table A.2. Lagrange-multiplier test for autocorrelation

Lag	Chi2	df	Prob>Chi2
1	19.4033	16	0.24831
2	24.7661	16	0.07406
3	36.6002	16	0.00239
4	26.1873	16	0.05145

Table A.3. Jarque-Bera test for normality

Equation	Chi2	df	Prob > chi2
D(Oil Production)	3.002	2	0.22289

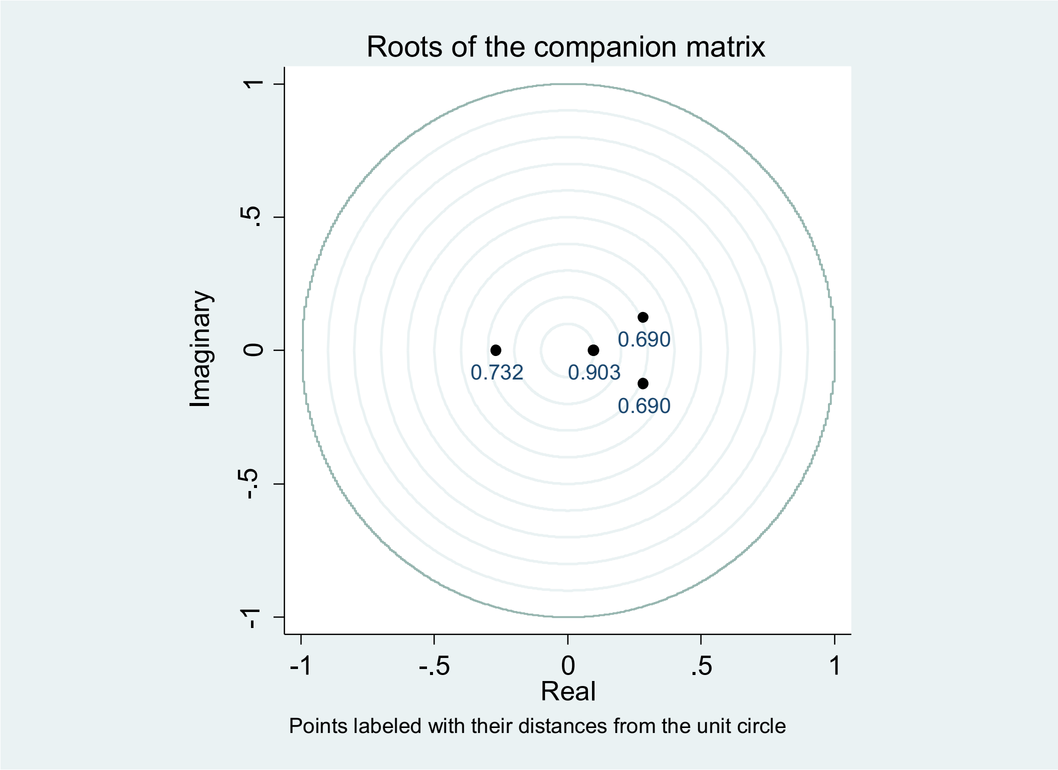

Figure A.1. Stability test of VAR estimates

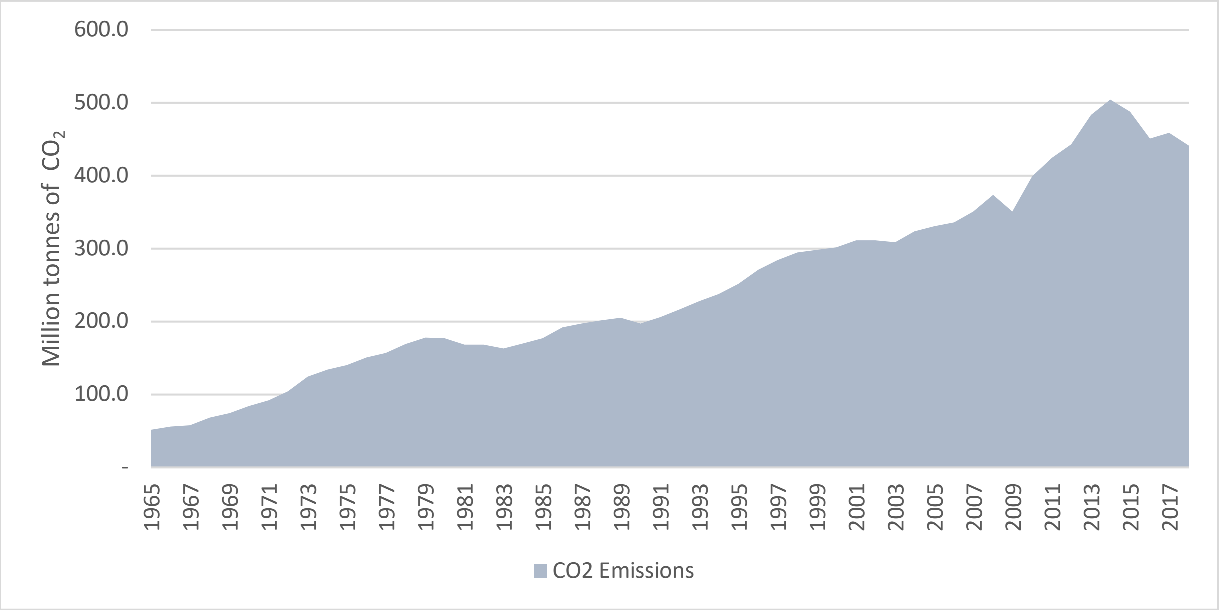

Figure A.2. Historical evolution of CO_2 emissions in Brazil

APPENDIX B

Stata Code

```
Declare Data as Time Series
tsset year, yearly

Describe Data
sum oilproduction ethanolproduction gasproduction crudeoilprices

Generate time trend
gen Trend=_n

Select optimal lag length
varsoc oilproduction gasproduction ethanolproduction crudeoilprices,
maxlag(4) exog (Trend)

ADF test for Unit root
dfuller oilproduction, trend lags (1)
dfuller ethanolproduction, trend lags (1)
dfuller gasproduction, trend lags (1)
dfuller crudeoilprices, trend lags (1)

First difference of ADF test
dfuller d.oilproduction, lags (1)
dfuller d.ethanolproduction, lags (1)
dfuller d.gasproduction, lags (1)
dfuller d.crudeoilprices, lags (1)

DF-GLS test for Unit root
dfgls oilproduction, trend ers
dfgls ethanolproduction, trend ers
dfgls gasproduction, trend ers
dfgls crudeoilprices, trend ers

First difference of DF-GLS test
dfgls d.oilproduction, ers
dfgls d.ethanolproduction, ers
dfgls d.gasproduction, ers
```

```
dfgls d.crudeoilprices, ers

Phillips-Perron test for Unit root
pperron oilproduction, trend
pperron ethanolproduction, trend
pperron gasproduction, trend
pperron crudeoilprices, trend

First difference of Phillips-Perron test
pperron d.oilproduction
pperron d.ethanolproduction
pperron d.gasproduction
pperron d.crudeoilprices

Perform Johansen cointegration test
vecrank oilproduction ethanolproduction gasproduction
crudeoilprices,trend(trend) lags (1) max

Unrestricted VAR model in first difference with a constant
var d.oilproduction d.ethanolproduction d.gasproduction d.crudeoilprices,
lags(1/1)

Unrestricted VAR model in first difference without a constant
var d.oilproduction d.ethanolproduction d.gasproduction d.crudeoilprices,
noconstant lags(1/1)

Impulse Response Function
irf create varbasic, set(varbasic, replace)
irf graph oirf, set(varbasic) irf(varbasic) impulse(D.ethanolproduction
D.gasproduction D.crudeoilprices) response (D.oilproduction) yline(0)

Diagnostic Tests
Test for Autocorrelation
varlmar, mlag(4)

Test for Stability
varstable, graph dlabel mcolor(black) msize(medsmall) msymbol(circle)
rlopts(lcolor(eltgreen)lwidth(medthin) lpattern(solid) connect(stairstep))
```

```
legend(off)


Normality test
varnorm, jbera
```