THE MARKET AND ENVIRONMENTAL EFFECTS OF ALTERNATIVE BIOFUEL POLICIES

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This dissertation analyzes market and environmental effects of alternative U.S. and Brazilian biofuel policies. Although we focus on corn- and sugarcane-ethanol, the advanced analytical framework can easily be extended to other biofuels and biofuel feedstocks, such as biodiesel and soybean. The dissertation consists of three chapters.

The first chapter develops an analytical framework to assess the market effects of a set of biofuel policies (including subsidies to feedstocks). U.S. corn-ethanol policies are used as an example to study the effects of biofuel policies on corn prices. We determine the 'no policy' ethanol price, analyze the implications for the 'no policy' corn price and resulting 'water' in the ethanol price premium due to the policy, and generalize the surprising interaction effects between mandates and tax credits to include ethanol and corn production subsidies. The effect of an ethanol price premium depends on the value of the ethanol co-product, the value of production subsidies, and how the world ethanol price is determined. U.S. corn-ethanol policies are shown to be a major reason for recent rises in corn prices. The ethanol policy-induced increase in corn prices is estimated to be 33 – 46.5 percent in the period 2008 – 2011.

The second chapter seeks to answer the question of what caused the significant increase in ethanol, sugar, and sugarcane prices in Brazil in the period 2010/11 to 2011/12. We develop a general economic model of the Brazilian fuel-ethanol-sugar complex. Unlike biofuel mandates

and tax exemptions elsewhere, Brazil's fuel-ethanol-sugar markets and fuel policies are unique in that each policy, in this setting, theoretically has an ambiguous impact on the market price of ethanol and hence on sugarcane and sugar prices. Our empirical analysis shows that there are two policies that seemingly help the ethanol industry but do otherwise in reality: a low gasoline tax and a high anhydrous tax exemption result in lower ethanol prices. On the other hand, as expected, higher mandates, gasoline prices, and tax exemptions for hydrous ethanol lead to higher ethanol and sugar prices. Eliminating Brazilian ethanol tax exemptions and mandates reduces ethanol prices by 21 percent in 2010-11, which is very similar to the estimated effects of U.S. ethanol policies in the same time period. However, the marginal changes in Brazilian policies on ethanol prices between 2010-11 and 2011-12 are small both individually and collectively. The observed market changes can only be explained by outward shifts in fuel transportation and sugar export demand curves, and reduced sugarcane supply due to bad weather.

In *the third chapter*, we investigate whether U.S. corn ethanol saves greenhouse gas emissions relative to the gasoline it is *assumed* to replace one-to-one (on an energy equivalent basis). This chapter shows that ethanol policies generate far greater carbon leakage in the fuel market than in the agricultural market, where leakage occurs in the form of land use change. Carbon leakage in the fuel market due to a tax credit is always greater than that of a mandate, while the combination of a mandate and subsidy generates greater leakage than a mandate alone. We show that corn-ethanol does not meet the U.S. EPA's sustainability threshold, regardless of the biofuel policy and whether one includes emissions from land use change. This result makes the controversy over how to measure land use change inconsequential.

BIOGRAPHICAL SKETCH

Dusan Drabik was born in Bardejov, Slovakia – then Czechoslovakia – on July 25, 1983. He attended the Ľudovít Štúr Grammar School in Michalovce and finished it in May 2001. In the fall of 2001, Dusan began his studies in agricultural economics at the Faculty of Economics and Management of the Slovak Agricultural University in Nitra (SAU). Due to his interest in agricultural economics and his academic performance, Dusan was offered a part-time research assistant position in the summer of 2005 to work on two EU-wide research projects. He graduated from the SAU with highest honors and earned his Ing. (M.S. equivalent) degree in May 2006. Starting from the fall of 2006, Dusan worked as a full-time research and teaching assistant at the Faculty of Economics and Management. Strongly encouraged by Jan Pokrivcak, a Cornell graduate, Pavel Ciaian, and Lubica Bartova, he decided to pursue his doctoral studies in agricultural economics in the Department of Applied Economics and Management – now the Dyson School of Applied Economics and Management – at Cornell University. Dusan arrived in Ithaca in August 2008, spent four and half wonderful years at Cornell, and defended his dissertation in December 2012.

To

my grandparents Mária Guľová and Ján Guľa

for the best childhood in the world, love, and

calluses from their hard work on the farm.

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I am also indebted to the other members of my Special Committee. I very much enjoyed working with David R. Just on the several papers we have co-authored so far and thank him for the encouragement during my Ph.D.; David was also very instrumental as the Director of Graduate Studies. I learned from Jon M. Conrad that every economic mathematical problem should have an economic interpretation, and I always admired his ability to see such interpretations even in very complex formulas. He also made me think more deeply about dynamic aspects of market phenomena and provided many ideas for my further research. Alan H. Matthews provided excellent comments on an earlier version of my dissertation; in addition to that, I greatly appreciate his assistance in rewriting my paper on the U.S. ‘Splash&Dash’ program which helped to calm dawn the not-so friendly reactions from the European Commission.

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God bless you all. Dusan

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CHAPTER 1

The Theory of Biofuel Policy and Food Grain Prices[1]

1. Introduction

The purpose of this paper is to develop a framework of analysis to assess the market effects of alternative biofuel policies, including subsidies to feedstocks. The model developed here uses U.S. corn-ethanol policy as an example, but the model can be applied to any country or biofuel policy. The analysis follows the pioneering work of de Gorter and Just (2008, 2009a,b), Lapan and Moschini (2009) and Cui et al. (2011). The key contributions of this paper are (1) a formula to determine the 'no policy' ethanol price; (2) the implications for the 'no policy' corn price and resulting 'water' in the ethanol price premium due to the policy[2]; (3) a generalization of the unique interaction effects between mandates and tax credits to include ethanol and corn production subsidies. All these issues have major implications for the market effects of ethanol policies, particularly on the level of corn prices, which is the focus of this paper.[3]

The consensus in the extensive literature on the causes of the recent increase in grain prices is that biofuel policies are only one of a multitude of contributing factors. For example, Headey and Fan (2010) attribute the price increase to a "near-perfect storm" of factors, and Abbott et al. (2008, 2009) argue that it has been a "complex maze of factors" where "one cannot with any precision partition the effects" and although biofuels are one "driver" among many, only 25 percent of biofuels' contribution to the price increase is due to biofuel policies.[4] However, Wright (2011) argues that most of the factors falling under the rubric of a "near-

[1] An earlier version of this chapter has been published as: Drabik, D. 2011. *The Theory of Biofuel Policy and Food Grain Prices*. Working Paper 2011-20. Charles H. Dyson School of Applied Economics and Management, Cornell University. December.
[2] 'Water' refers to the gap between the 'no policy' ethanol price and the intercept of the ethanol supply curve.
[3] The analysis in this paper has also implications for environmental aspects of ethanol policy; we do not analyze those here, however.
[4] Abbott et al. (2008, 2009) and Hochman et al. (2011) provide extensive surveys on the different papers analyzing the effects of biofuel policies on food grain prices.

perfect storm" do not in the aggregate explain the recent grain price spikes. He concludes that the two recent grain price spikes were caused by new demand for biofuels.

Because the demand for biofuels is greatly influenced by existing biofuel policies, the purpose of this paper is to develop an analytical framework to analyze the linkage between biofuel policies and food grain commodity prices. The theory explains the price linkages among biofuels, their feedstocks, and fossil fuel (oil), under alternative policies. It also provides the means to determine which policy—a tax credit or a blend mandate— is determining the ethanol price in the United States or in the rest of the world.

This paper extends the previous literature (e.g., de Gorter and Just 2008, 2009a,b; Yano et al. 2010) in several ways. First, we explicitly take into account the role of the ethanol co-product in modeling the price (i.e., vertical) and quantity (i.e., horizontal) links between the fuel and corn markets. Because the ethanol co-product (Dried Distillers Grains with Solubles) is a very close substitute to yellow corn in feed consumption, DDGS replaces yellow corn when it is returned to the corn market, and the ethanol industry effectively obtains more feedstock than initially available. We call this the 'recycling effect' of the ethanol co-product. The recycling effect has important implications not only for the ethanol supply curve *per se* – it increases its elasticity – but also for the analysis of the price effects of biofuel policies and the volatility of corn prices due to exogenous shocks in the oil and/or corn markets.

Second, unlike the current literature, which has focused primarily on the analysis of biofuel mandates, blender's tax credits and ethanol import tariffs, we model and analyze two additional policies: ethanol and corn production subsidies.[5] In this paper, we do not analyze the effects of the import tariffs, but we extensively study the corn price effects of the remaining four

[5] This is surprising, given that corn production subsidies in the United States totaled 21.1 billion dollars from 2006 to 2010 (Environmental Working Group) and ethanol production subsidies are estimated to be 1.35 billion dollars in 2008 alone (Koplow 2009).

biofuel policies (blend mandate, blender's tax credit, ethanol and corn production subsidies) and their interactions. We find that if the biofuel mandate binds (i.e., it determines the ethanol market price), the other three policies actually subsidize consumption of the fuel blend, so these policies effectively subsidize gasoline consumption. However, the market mechanism differs between the policies' effects on ethanol and corn prices. For example, a blenders' tax credit increases the ethanol market price, while the ethanol production subsidy reduces it; nevertheless, both policies increase the corn market price.

Third, we revisit the concept of 'water' in the biofuel price premium, which exists when the intercept of the ethanol supply curve is above the ethanol price that would prevail without any of the four biofuel policies in place. We find that the previous literature has ignored the effect of the volumetric fuel tax on 'water' and thus underestimated the rectangular deadweight costs of biofuel policies. We also find that the ethanol price premium, defined as the difference between the observed corn price and a hypothetical ethanol price (in dollars per bushel) that would cause consumers to purchase ethanol in the absence of biofuel policies, is high because of (1) lower mileage per gallon of ethanol relative to gasoline and (2) a 'penalty' on ethanol due to the volumetric fuel tax. For example, we estimate the ethanol price premium to be $3.51/bu in 2008, which is 83 percent of the ethanol market price. However, the impact of the price premium on the corn market price is decreased by the 'water' which exists in the ethanol price premium; although the impact of biofuel policies on the corn price is significant, the impact is smaller than it would be if there were less 'water'.

The paper is outlined as follows. The next section develops the link between ethanol and corn prices (i.e., the vertical link). The link between corn and ethanol quantities (i.e., the horizontal link) is analyzed in Section 3 where we also explain the 'recycling effect' of the ethanol by-product. In Section 4, we provide an intuitive graphical analysis of the effects of various combinations of the mandate and tax credit with production subsidies on both ethanol and corn prices. In Section 5, we revisit the concept of 'water' in a biofuel price premium and show why the previous literature has underestimated the rectangular deadweight costs associated with 'water.' Section 6 provides an empirical illustration of our theoretical results. The last section provides concluding remarks.

2. The Link between Ethanol and Corn Prices

One bushel of yellow corn produces $\beta = 2.8$ gallons of ethanol (Eidman 2007). The lower energy content of ethanol relative to gasoline translates into lower mileage from ethanol, meaning that one gallon of ethanol yields only $\lambda = 0.7$ times the miles obtained from one gallon of gasoline (de Gorter and Just 2008).[6] Therefore, one bushel of yellow corn yields $\lambda\beta = 1.96$ gasoline miles-equivalent gallons (GMEGs) of ethanol.

When a bushel of yellow corn is processed into ethanol, $\gamma = 0.304$[7] bushels of a co-product known as Dried Distillers Grains with Solubles (DDGS) are also produced. The DDGS are a valuable substitute for yellow corn in non-ethanol uses of corn, especially as animal feed. The market price of the co-product has historically differed from that of yellow corn. Denoting P_C as the corn market price and r as the relative price of DDGS and yellow corn, the price of DDGS is $r \times P_C$. Let the processing cost associated with one GMEG of ethanol be c_0. Following de Gorter and Just (2008) and Cui et al. (2011), we assume that c_0 is a fixed constant. Ethanol is assumed to be produced by perfectly competitive firms that use a constant returns to scale

[6] Using average EPA data, de Gorter and Just (2008) take into account the difference between ethanol and gasoline on the basis of miles traveled per gallon of each fuel, rather than by the energy content of the two fuels. This yields a value of $\lambda = 0.7$. If one simply uses the differential energy content, then the value of λ equals 0.66 (=75,700 Btu/115,000 Btu; Btu – British thermal unit) (http://bioenergy.ornl.gov/papers/misc/energy_conv.html). Most of the literature uses the latter value.

[7] Ethanol production generates approximately 17 pounds of DDGS per bushel of corn (56 pounds); hence, $\gamma = 17/56 \approx 0.304$ (Cui et al. 2011).

technology. These assumptions about the technology and market structure imply zero marginal profits; the zero-profit condition is equivalent to the following relationship between ethanol and corn prices:

$$P_E - \frac{1}{\lambda\beta}P_C + \frac{r\gamma}{\lambda\beta}P_C - c_0 = 0 \qquad (1)$$

where P_E denotes the price received by ethanol producers (in dollars per GMEG). The second term in equation (1) represents the cost of yellow corn needed to produce one GMEG of ethanol; the third term is the revenue received for the ethanol co-product; the last term is the processing cost.

By rearranging equation (1), we obtain the link between ethanol and corn prices[8]

$$P_C = \frac{\lambda\beta}{1-r\gamma}\left(P_E - c_0\right) \qquad (2)$$

Under the given ethanol production assumptions, equation (2) governs the ethanol-corn price relationship under any biofuel policy.

How Well Does the Theoretical Corn-Ethanol Price Linkage Reflect Reality?

The corn-ethanol price relationship (2) hinges on the assumption that ethanol producers operate under zero profits. Although this assumption is justifiable in the long run when the industry is likely to be in equilibrium, the observed data for recent years reveal that ethanol producers mostly earn positive profits. Given this discrepancy, which could be due to either capacity constraints or a short operation period for ethanol plants, any further analysis requires a comparison of how well the theoretical corn price predicts reality.

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[8] Alternatively, the zero profit condition per bushel of yellow corn is: $\lambda\beta P_E - P_C + r\gamma P_C - \tilde{c}_0 = 0$, where $\tilde{c}_0$ denotes a processing cost per bushel of yellow corn. The corn market price can then be expressed as: $P_C = \left(\lambda\beta P_E - \tilde{c}_0\right)/\left(1-r\gamma\right)$. Comparing the preceding expression with that in equation (2) yields: $\tilde{c}_0 = \lambda\beta c_0$.

The first column of Table 1 shows the average profit per gallon of ethanol production by year. We use monthly data on ethanol operating margins from March 2005 to December 2011, from the Center for Agricultural and Rural Development (CARD) of Iowa State University.[9]

Table 1. Comparison of the Observed and Predicted Ethanol-Corn Price Conversion Factors

Year	Profit per gal. (π)	$P_C/(P_E-c_0)$	$P_C/(P_E-c_0-\pi)$	$\beta/(1-r\gamma)$
	(1)	(2)	(4)	(6)
2005*	0.48	2.55	4.32	4.27
2006	1.21	1.44	4.15	3.96
2007	0.32	2.95	3.91	3.78
2008	0.07	3.62	3.80	3.84
2009	0.11	3.53	3.91	3.78
2010	0.08	3.60	3.86	3.85
2011	0.13	3.48	3.72	3.92

Note: * March - December
** The ethanol production subsidy is considered only for 2008 - 2011.
The values are simple averages for a given year. They are not adjusted for mileage of ethanol.
Source: Calculated based on "Historical Ethanol Operating Margins" data from table "All Historical Data", http://www.card.iastate.edu/research/bio/tools/hist_eth_gm.aspx

Profits are significantly positive in the first three years when many ethanol production facilities opened. Overall, however, profits tend to decline over the sample period, reaching almost zero in 2010. To test the validity of the relationship in (2) empirically, we rewrite it as

$$\frac{P_C}{P_E - c_0} = \frac{\lambda\beta}{1 - r\gamma} \tag{3}$$

The left-hand side of equation (3) is solely determined by the observables, while the right-hand side consists of fixed parameters[10], except for the relative price of DDGS to ethanol, r, because this may vary over time. Since CARD does not report prices for DDGS, we use data for Lawrenceburg, Indiana as reported by the USDA AMS. The processing cost c_0 includes capital costs of \$0.25 per gallon and other operating costs which average\$0.52 per gallon over the period of observation. All data reported in Table 1 pertain to a physical gallon of ethanol and are not adjusted for energy content. To obtain GMEG counterparts of the reported data, the values in

[9] http://www.card.iastate.edu/research/bio/tools/hist_eth_gm.aspx
[10] These parameters are assumed to be fixed at least over the period analyzed.

the first column should be divided by $\lambda = 0.7$, and those in the remaining columns should be multiplied by $\lambda = 0.7$.

The second column of Table 1 corresponds to the left-hand side of equation (3). Compare this to the last column, which represents the predicted vertical (i.e., price) ethanol-corn conversion factor. The discrepancies are comparatively large, especially for 2005 to 2007. These discrepancies can be explained by the observed non-zero profits. After 2008, profits are close to zero and the values in the second and forth columns get much closer. Indeed, if we treat the observed profits as measurement error, and we take this into account by adjusting the left-hand side of equation (3) (with the corrected values shown in the third column), then in the period 2008 – 2011, both sides of equation (3) are almost the same (see the highlighted part of Table 1).[11] The remaining discrepancies are attributable to different measurement locations for the corn and DDGS prices – Iowa and Indiana, respectively. The good match between the predicted and observed corn prices in the period 2008 – 2011 is advantageous because we seek to analyze the recent increases in food grain commodity prices which manifested mainly in 2008 and 2011.

3. The Link between Ethanol and Corn Quantities

We have shown that, under plausible assumptions, a long run relationship between corn and ethanol prices can be expected. To derive the price link, we assumed that 2.8 gallons of ethanol (1.96 GMEGs) are produced from one bushel of yellow corn. Is this technological parameter the *only* conversion factor that governs the quantity link between the corn and ethanol markets? The answer is ‘yes’ if we analyze the *observed quantity* of corn used in ethanol production, but it is ‘no’ if we wish to consider the *intended quantity* of corn to be used in ethanol production. The reason is intuitive: because the ethanol co-product (DDGS) is a very close substitute for yellow

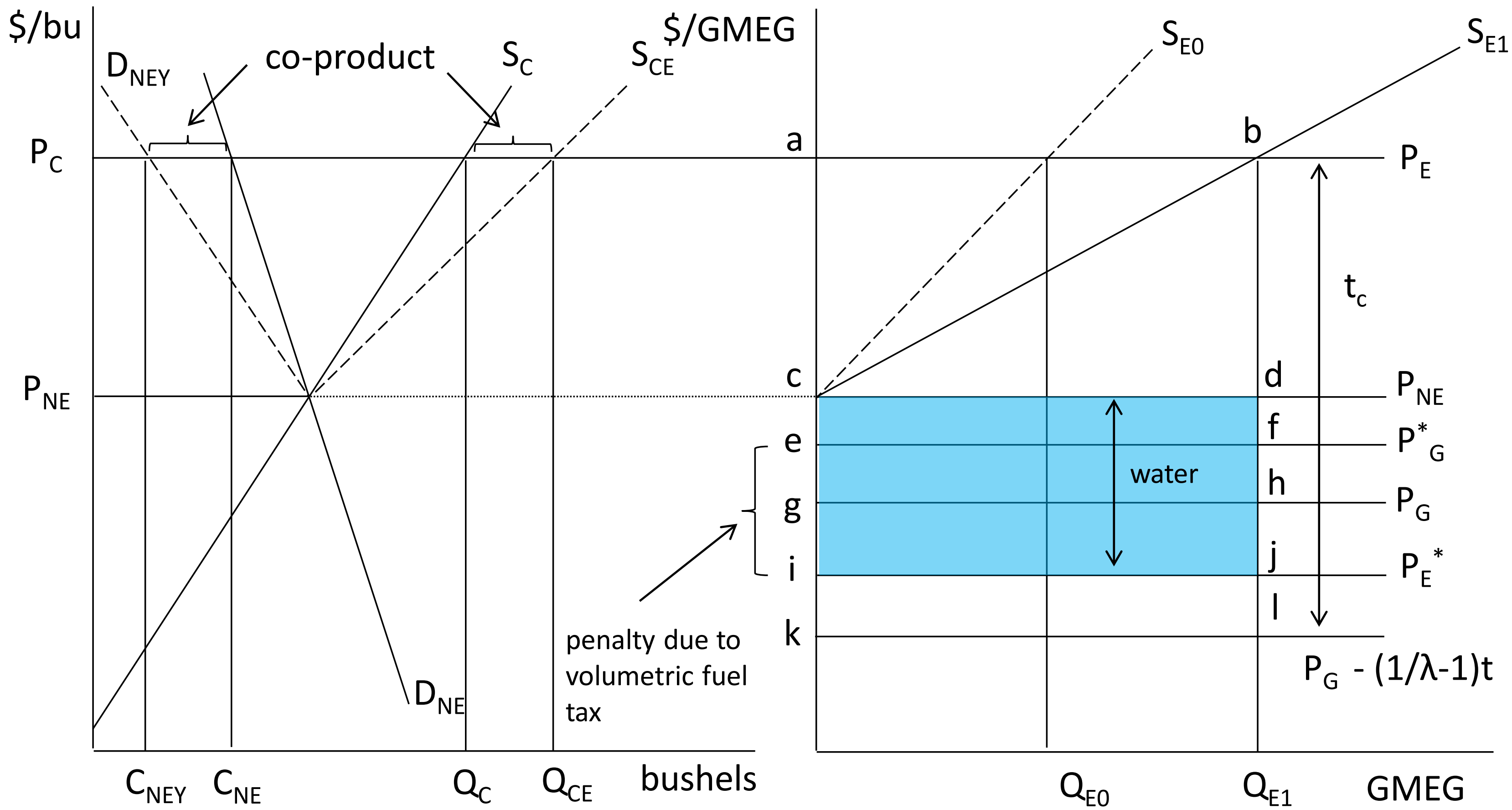
[11] Mallory et al. (2010) propose that the link between the corn and the energy sectors is manifested in the prices of commodity futures with at least one year until maturity. Although we use spot prices to test the predictive ability of equation (2), we obtain a close match between the predicted and observed (spot) prices.

corn in feed or food consumption, a market effect of DDGS being returned to the corn market is that it replaces yellow corn; since DDGS decreases the amount of yellow corn consumed for non-ethanol uses, more yellow corn is available for ethanol production. This means that the one bushel of yellow corn "initially intended" to be used for ethanol effectively produces more than 2.8 gallons of ethanol. We call this the *recycling effect* of the ethanol co-product. On the other hand, the ratio of ethanol production and the quantity of corn used for ethanol is empirically shown to be very close to 2.8; this is because the observed data are inclusive of the recycling effect. We now explain these important concepts in greater detail.

Consider the corn market depicted in the first panel of Figure 1. If no ethanol is produced, corn is only used as feed or food. In this case, the non-ethanol corn market price P_{NE} is where the supply curve of yellow corn S_C intersects the demand curve for non-ethanol corn D_{NE}. The demand curve represents aggregate (domestic and export) demand for feed/food corn facing U.S. farmers. At corn prices greater than P_{NE}, there is an excess supply of yellow corn, which can be feedstock for ethanol production. Notice that because yellow corn and DDGS are very close substitutes, the demand curve D_{NE} should be thought of as demand for yellow corn and possibly DDGS as well.[12] In the absence of ethanol production, D_{NE} denotes demand for yellow corn, but if ethanol is produced, D_{NE} represents aggregate demand for yellow corn and DDGS.

[12] Typically, yellow corn and DDGS differ in their nutritional value. This makes them imperfect substitutes. In order to model the market effects of the ethanol co-product consistently, we assume the relative price of DDGS and yellow corn reflects the nutritional differences. Therefore, after adjusting the physical quantity of DDGS by the relative price, yellow corn and DDGS are modeled as perfect substitutes.

Figure 1. Equilibrium in the Corn and Ethanol Markets with a Binding Blender's Tax Credit



Assume that an ethanol blenders' tax credit $\tilde{t}_c$ determines the ethanol market price $\tilde{P}_E$, where the tilde sign denotes that the blenders' tax credit and ethanol market price are expressed in dollars per gallon of ethanol. Following de Gorter and Just (2008), the ethanol market price under a binding tax credit is

$$\tilde{P}_E = \lambda P_G - (1-\lambda)t + \tilde{t}_c \tag{4}$$

where P_G is the market price of gasoline (oil) and t is a volumetric fuel tax. Dividing equation (4) by λ, similarly to Cui et al. (2011), we express the ethanol market price in dollars per GMEG

$$P_E = P_G - \left(\frac{1}{\lambda} - 1\right)t + t_c \tag{5}$$

where $P_E = \tilde{P}_E / \lambda$ and $t_c = \tilde{t}_c / \lambda$. The ethanol market price given by equation (5) is depicted in the second panel of Figure 1 (and also in Figures 2 and 3).[13] Equations (4) and (5) reflect the idea that if consumers are free to choose between ethanol and gasoline for fuel, and if they buy fuel based on the miles traveled that it provides, then they will buy ethanol only if its price (adjusted for the fuel tax and tax credit) per GMEG equals the price of gasoline. (See section 5 for more details).

Using equation (2), we can convert the ethanol price P_E to the corn price P_C, equal to the price of ethanol in dollars per bushel, P_{Eb}.[14] If the corn market price is directly linked to the ethanol price through equation (2) and the latter is linked to the gasoline price through equation (5), then any supply or demand shifts in the corn market[15] have no effect on the corn price unless

[13] The graphical analysis in Figures 2 to 7 assumes that the gasoline supply is perfectly elastic. We relax this assumption in the appendices.
[14] To avoid the "discontinuities" along the vertical axis in the second panel of our figures (because the price conversion factor is greater than one), we assume that the corn market price is the same as the ethanol price, except for their different units. This simplifies the graphical exposition but has no impact on the qualitative results.
[15] These shifts can be, for example, due to exchange rate depreciation, bad weather, income growth in developing countries, or biodiesel mandates that increase soybean prices (Heady and Fan 2010; Abbott et al. 2008, 2009; Hochman et al. 2011).

they also affect oil prices. This is the situation which existed when the now phased-out U.S. tax credit was determining the ethanol price prior to 2008. The only effect these shifts have when ethanol prices are tied directly to oil prices through the tax credit is to change the non-ethanol corn price (i.e., P_{NE}) and hence the level of 'water'[16] in the ethanol price premium due to the tax credit. This point seems to be forgotten in the debate about the influence of the ethanol tax credit or ethanol price premium due to the mandate on corn prices.

In Figure 1, the quantity of yellow corn produced at price P_C is Q_C and the amount to be consumed for non-ethanol uses is C_{NE}.[17] Thus, for any price P_C (which is linked to the ethanol price), the horizontal difference between S_C and D_{NE} in the first panel of Figure 1 represents the quantity of yellow corn for ethanol production. Multiplying this quantity by the parameter β = 2.8, we obtain a corresponding ethanol supply curve S_{E0}, constructed under the assumption of no ethanol co-product. Note that the intercept of S_{E0}, adjusted for units, corresponds to P_{NE}. Without any co-product, the quantity of ethanol would be Q_{E0}, equal to β times the distance $C_{NE}Q_C$. However, we must take the co-product of ethanol production into consideration when modeling the corn market.

The high degree of substitutability between DDGS and yellow corn (after we account for their slight difference in nutritional value) implies a one-to-one replacement of yellow corn, which would otherwise be consumed as feed, by the ethanol co-product. As noted above, we call this the 'recycling effect' of the ethanol co-product. In a first step of recycling, DDGS enter the feedstock and the yellow corn it displaces is made available for ethanol production. This process continues until the marginal amount of yellow corn that is displaced by DDGS and made

[16] The concept of 'water' in a biofuel policy is explained in section 5.
[17] At this stage, we aim to determine the quantity of yellow corn to be used in ethanol production at price P_E. When ethanol is produced and the co-product returned in the corn market, then D_{NE} represents demand for corn equivalent, and the implicit demand for yellow corn for non-ethanol use is derived.

available for ethanol production is approximately zero.[18] In equilibrium, one initial bushel of corn is associated with $1/(1–r\gamma) \approx 1.35$ bushels of yellow corn processed for ethanol.[19] By definition, the size of the recycling effect is equal to the total quantity of the co-product in equilibrium; that is, $r\gamma/(1–r\gamma) = 0.35$ additional bushels of corn for non-ethanol consumption are associated with one initial bushel of yellow corn.[20]

After accounting for the recycling effect, one initial bushel of yellow corn yields $\lambda\beta/(1-r\gamma) = 2.65$ GMEGs of ethanol.[21] Therefore, the equilibrium supply of ethanol, denoted by S_{E1} in the second panel of Figure 1, is given by

$$S_E\left(P_E\right) \equiv \frac{\lambda\beta}{1-r\gamma}\left(S_C\left(P_C\right) - D_{NE}\left(P_C\right)\right) \tag{6}$$

where the ethanol and corn prices are linked through equation (2). The implicit demand curve for yellow corn D_{NEY} in the first panel of Figure 1 is derived by subtracting the quantity of the co-product from D_{NE} at any corn price above P_{NE}. By construction, D_{NEY} is flatter than D_{NE}.

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[18] Formally, denote X as the initial quantity of yellow corn for ethanol production. The physical quantity of the co-product is then γX. Adjusting this quantity for the nutritional value, we obtain $r\gamma X$. This is the quantity that replaces yellow corn one-to-one. Thus, the additional quantity of yellow corn is $r\gamma X$. The physical quantity of the co-product corresponding to the additional yellow corn is $r\gamma^2 X$, which diverts another $r^2\gamma^2 X$ bushels of yellow corn to ethanol production. This process continues until the ethanol co-product replaces no additional corn. As a result, the total quantity of yellow corn actually used in ethanol production is $X + r\gamma X + r^2\gamma^2 X + ... = X/(1-r\gamma)$, while the quantity of (corn-equivalent) co-product is $r\gamma X + r^2\gamma^2 X + ... = r\gamma X/(1-r\gamma)$. This process is bound to converge because $0 < r\gamma < 1$.

[19] In the illustrative calculations of the recycling effect, we use data for 2009.

[20] The analysis above needs to be adjusted if there is an upper bound on the share of the co-product in D_{NE}, perhaps because of some technological limits. Denote this upper bound as $\bar{\theta}$. As long as the equilibrium quantity of the co-product satisfies $\left[\gamma/(1-r\gamma)\right] \times \left[S_C\left(P_C\right) - D_{NE}\left(P_C\right)\right]/D_{NE}\left(P_C\right) < \bar{\theta}$, the technological constraint is not binding, and the recycling effect is fully effective, meaning that the maximum quantity of ethanol is produced from a given quantity of yellow corn. However, if in a potential equilibrium: $\left[\gamma/(1-r\gamma)\right] \times \left[S_C\left(P_C\right) - D_{NE}\left(P_C\right)\right]/D_{NE}\left(P_C\right) \geq \bar{\theta}$, then the technological constraint binds, and the maximum quantity of ethanol produced is: $\lambda\beta \times \left(\bar{\theta} D_{NE}\left(P_C'\right) + \left[S_C\left(P_C'\right) - D_{NE}\left(P_C'\right)\right]\right)$, which is always less than the quantity given by identity (6). We use the primes on the corn price to indicate that the corn price would differ from the case when the constraint is not binding. Whether the constraint is binding or not is an empirical question.

[21] If not adjusted for the relative miles traveled per gallon of ethanol and gasoline, one bushel of yellow corn produces 3.78 gallons of ethanol.

Alternatively, the effects of the co-product on the corn market can be viewed as a pivot of the corn supply curve S_C; DDGS increase the supply of corn in corn-equivalent (nutritional units). Thus, the curve S_{CE} in the first panel of Figure 1 denotes the quantity of corn-equivalent available at any corn price above P_{NE} and is constructed as the horizontal summation of S_C and the corresponding quantity of the co-product. Mathematically,

$$S_{CE}\left(P_C\right) \equiv S_C\left(P_C\right) + \frac{r\gamma}{1-r\gamma}\left(S_C\left(P_C\right) - D_{NE}\left(P_C\right)\right) \tag{7}$$

for $P_C \geq P_{NE}$. Since $dS_{CE}/dP_C > dS_C/dP_C \geq 0$, for a given corn price, the supply curve of corn-equivalent is always flatter than the supply of yellow corn.

A closer inspection of equations (2) and (6) suggests that biofuel policies affect ethanol production or corn production and consumption indirectly: ethanol prices affect corn prices; corn prices affect corn production and feed/food consumption; corn supply and non-ethanol corn demand together determine the quantity of ethanol produced.

To illustrate the concepts related to the horizontal (quantity) link between corn and ethanol, we use data from the USDA for marketing years 2005/06 to 2009/10 (seen in columns one through five in Table 2).[22]

[22] The data come from the USDA's WASDE (World Agricultural Supply and Demand Estimates) reports.

Table 2. Estimated Elasticity of the Implied Ethanol Supply Curve

	Million bushels				Million gallons		
	Supply[a]	Domestic non-ethanol use[b]	Exports[c]	Ethanol[c] Q_{CE}	Ethanol prod.[d] Q_E	Q_E/Q_{CE}	Elasticity of ethanol supply[e]
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
2005-06	11270	7533	2134	1603	4500	2.81	10.86
2006-07	11210	6966	2125	2119	5883	2.78	8.06
2007-08	12738	7251	2437	3049	8367	2.74	6.50
2008-09	12057	6498	1849	3709	10305	2.78	4.57
2009-10	13065	6495	1980	4591	12670	2.76	4.09

Source: Calculated based on

[a] Supply = production + imports + beginning stocks - ending stocks; USDA WASDE reports, various years.

[b] Domestic non-ethanol use = feed and residual + food, seed and industrial - ethanol for fuel; USDA WASDE reports, various years.

[c] USDA WASDE reports, various years.

[d] EIA - Table 10.3 Fuel Ethanol Overview, http://www.eia.gov/totalenergy/data/monthly/index.cfm#renewable

[e] Formula for elasticity of the ethanol supply curve is in Appendix 3.

All reported data relate to yellow corn. The quantities of domestic non-ethanol corn and corn for exports combined represent the quantity C_{NEY} in the first panel of Figure 1. Similarly, the observed quantity of corn for ethanol production corresponds to the distance $C_{NEY}Q_C$; in order to compute the counterfactual quantity of corn that would be processed into ethanol in the absence of the co-product, the values in the fourth column of Table 2 would be multiplied by $(1 - r\gamma) \approx 0.74$.

The sixth column presents empirical estimates of the corn-ethanol quantity conversion factor, β, which are obtained by dividing the actual ethanol production by the quantity of corn used for ethanol. The empirical ratio ranges between 2.74 and 2.81 and closely resembles the commonly-used conversion factor of $\beta = 2.8$. This is in accord with our earlier hypothesis that the distance $C_{NEY}Q_C$ in Figure 1 represents the effective quantity of corn used for ethanol production (i.e., it reflects the recycling effect).

The last column in Table 2 presents estimates of the elasticities of the ethanol supply curve S_E.[23] Consistent with the recent literature (de Gorter and Just 2009b; Cui at al. 2011), we assume that the elasticities of corn supply, domestic demand and foreign demand are equal to 0.23, – 0.2 and –1.5, respectively. In Table 2, the ethanol supply curve becomes less elastic over time, largely because the share of corn supply used for ethanol is increasing.

4. Ethanol and Corn Production Policies Combined

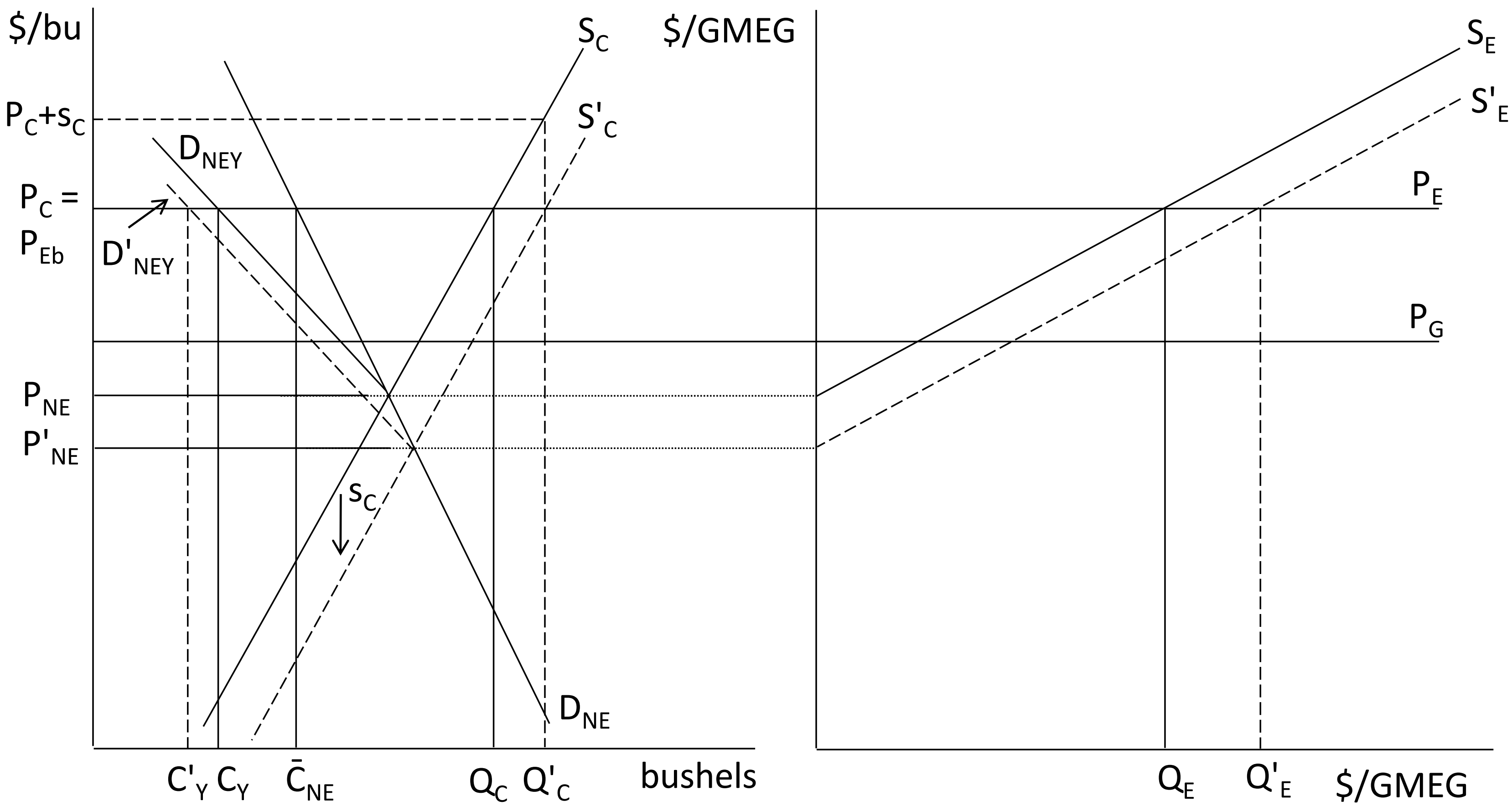
To keep the graphical analysis as simple as possible, we analyze at most two policies at a time and abstain from depicting the supply of corn-equivalent, S_{CE}. More specifically, Figures 2 and 3 investigate the effects of combining a binding tax credit with a corn production subsidy or an ethanol production subsidy, respectively. Figure 4 analyzes the impact of a binding ethanol blend mandate alone; Figures 5 through 7 analyze the binding ethanol blend mandate in combination with a tax credit, corn production subsidy, or ethanol production subsidy, respectively. In all figures, we assume a fixed oil (gasoline) price; we assume that the demand for non-ethanol corn is the horizontal sum of domestic and export demand for corn, inclusive of the ethanol co-product. We analyze an endogenous oil price in an extended model presented in the appendices. In the numerical simulations we will assume an endogenous gasoline (oil) price, international trade in gasoline (oil) and corn, as well as a fuel tax in the domestic economy, but these features are omitted from the graphical representation of the model for tractability.

A Blender's Tax Credit with a Corn Production Subsidy

Consider a corn production subsidy s_C that lowers the marginal cost of yellow corn production in the first panel of Figure 2; this is depicted as a shift of S_C to S'_C. As a result, the threshold price of corn for ethanol production to occur decreases from P_{NE} to P'_{NE}, giving rise to a new supply of ethanol S'_E. Given that the ethanol market price is constant (since it is linked to

[23] The formula for the elasticity of the ethanol supply curve is derived in Appendix 3.

Figure 2. Equilibrium in the Corn and Ethanol Markets with a Binding Blender's Tax Credit and a Corn Production Subsidy



the oil price), the corn production subsidy causes ethanol production to increase from Q_E to Q'_E. One might ask, why should ethanol producers produce more ethanol if they receive the same market price?

To answer this question, note that without the corn production subsidy, the quantity of corn for ethanol production is given by the distance C_YQ_C, which corresponds to the excess corn supply at price P_C. The corresponding profits are given by

$$\pi = \left(\lambda\beta P_E - P_C + r\gamma P_C - \tilde{c}_0\right) \times C_Y Q_C \tag{8}$$

and are equal to zero because of the zero-profit condition in ethanol production. (See the discussion of equation (1)).

Suppose for a moment that an ethanol producer does not change its level of production when the subsidy is introduced. Demand for corn is still equal to C_YQ_C. With the subsidy, however, the same quantity of corn can be purchased at a lower price denoted by P'_C (not shown in Figure 2); the market price of ethanol remains unchanged at P_E. Hence, under the corn production subsidy the profits for an ethanol producer which does not change its production level when the subsidy is introduced are

$$\pi' = \left(\lambda\beta P_E - P'_C + r\gamma P'_C - \tilde{c}_0\right) \times C_Y Q_C > 0 \tag{9}$$

because $P'_C < P_C$.

The positive economic profits in (9) imply that new producers will enter the market or the incumbent producers will expand their production; more corn will be consumed for ethanol production. Competition ensures that the producers will bid up the price of corn back to P_C as more corn is processed for ethanol.

Because the corn market price in Figure 2 does not change with the corn production subsidy, consumption of corn for feed/food use does not change either. This situation motivates the notion of the recycling effect because it is probably the only explanation for how the corn and ethanol markets can be in equilibrium under this situation. The additional corn produced as a result of the corn production subsidy shifts to ethanol production, followed by yellow corn obtained by changing the composition of non-ethanol consumption due to additional quantity of the co-product induced by the corn production subsidy.

In the fuel market, the corn production subsidy does expand the supply of ethanol (curve S'_E), but the ethanol market price does not change unless the increase in ethanol production affects the world oil price (we relax the assumption of an exogenous gasoline price in the appendices). Corn producers receive the market price of corn plus the corn production subsidy. Note also that because the corn production subsidy expands ethanol production, more co-product is returned to the corn market which crowds out yellow corn from feed/food consumption; hence the total consumption of yellow corn decreases to C'_Y.

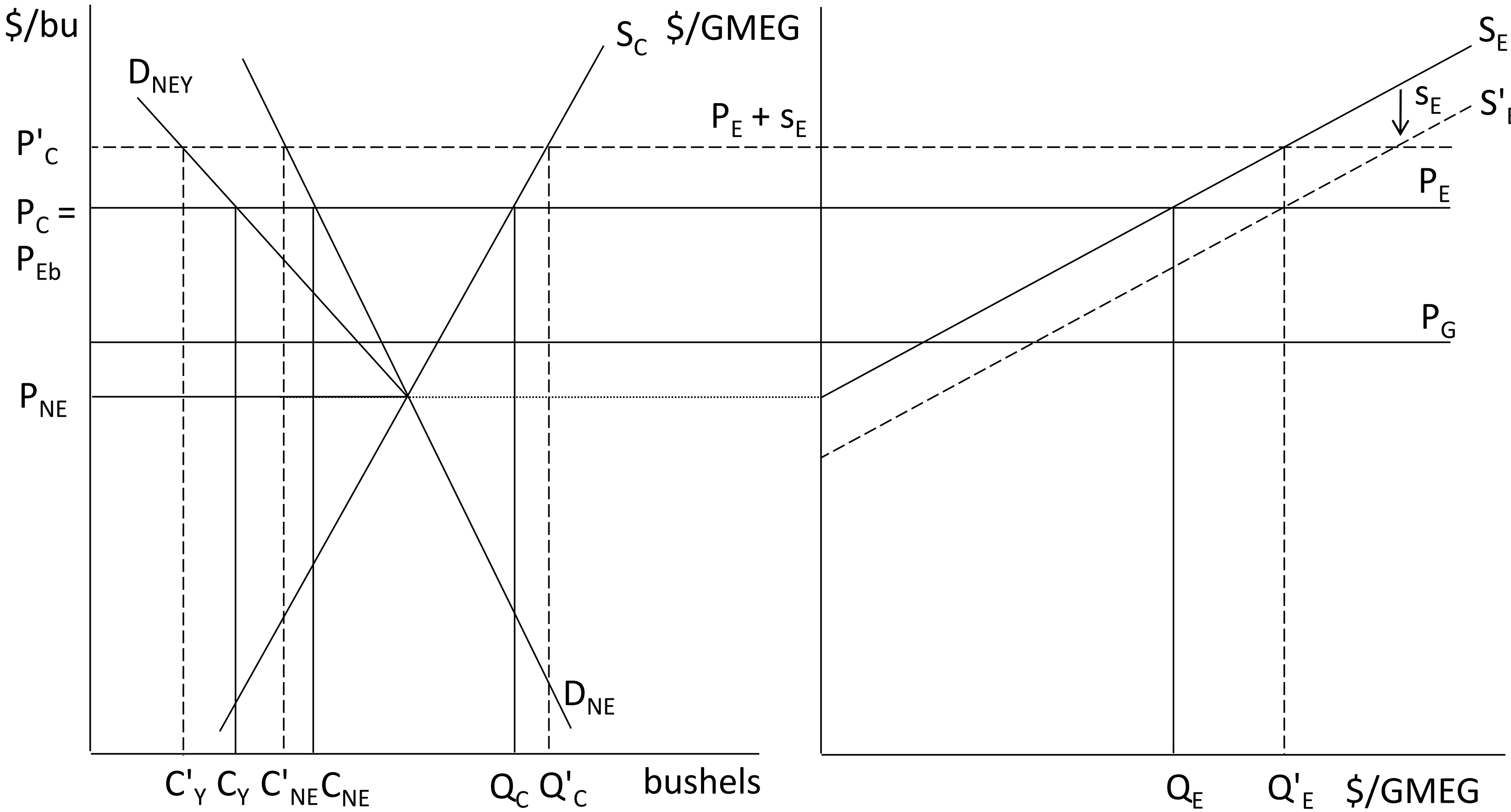
A Blender's Tax Credit and an Ethanol Production Subsidy

The market effects of an ethanol production subsidy s_E are presented in Figure 3. The subsidy reduces the marginal cost of ethanol production, and the vertical shift of the ethanol supply curve from S_E to S'_E in the second panel of Figure 3 expands ethanol production from Q_E to Q'_E. Ethanol producers receive a price that exceeds the ethanol market price by the full amount of the subsidy— i.e., they receive $P_E + s_E$. However, since ethanol producers earn zero profits, the subsidy is essentially a transfer to corn producers, who expand their production from Q_C to Q'_C. Consumers of corn for feed/food are worse off because of an increase in the corn market price from P_C to P'_C in the first panel of Figure 3.[24]

The comparative statics for the blender's tax credit and ethanol production subsidy model

[24] As the consumption of non-ethanol corn contracts, it is more likely that the technological constraint considered in footnote 24 will be binding, if it exists.

Figure 3. Equilibrium in the Corn and Ethanol Markets with a Binding Blender's Tax Credit and an Ethanol Production Subsidy



with an endogenous gasoline price and a binding tax credit are presented in Table 3 (see Appendix 1 for details). The tax credit decreases the gasoline and fuel prices and increases the ethanol and corn prices. These price effects occur because the tax credit induces greater ethanol production and hence also greater corn production. Ethanol crowds out gasoline in the fuel blend, so gasoline production declines and the gasoline price decreases. As we show in Appendix 1, under a binding tax credit the fuel price equals the sum of the gasoline price and the fuel tax. A corn production subsidy has a negative effect on all prices. It decreases the marginal cost of corn production, and ethanol production expands as the corn price decreases. The ethanol production subsidy lowers the marginal cost to fuel blenders by reducing the ethanol market price, and it expands ethanol production because producers receive the ethanol market price plus the subsidy. The ethanol production subsidy increases the corn price because the corn price is linked, as per equation (2), to the price received by ethanol producers.

Table 3. Comparative Statics Results for a Binding Tax Credit

		Effect on			
		P_G	P_E	P_F	P_C
Change in	t_c	–	+	–	+
	s_C	–	–	–	–
	s_E	–	–	–	+

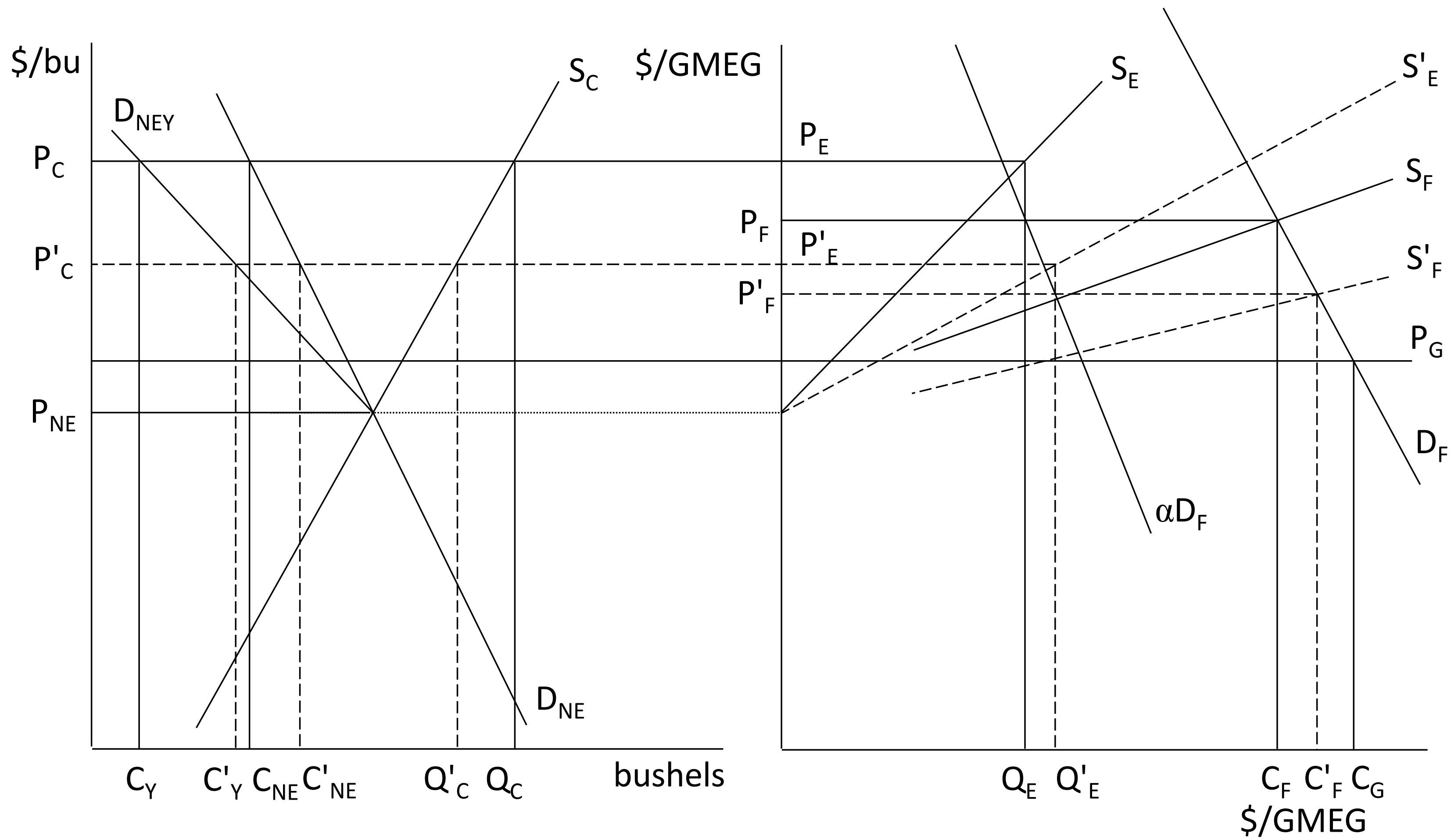
Source: Appendix 1

Although a blender's tax credit is an ethanol consumption subsidy, it has the same quantitative effect on the corn price as an ethanol production subsidy. This occurs even though the former increases the ethanol market price and the latter reduces it.

A Biofuel Blend Mandate

Instead of focusing on the economics of a biofuel blend mandate depicted in the second panel of Figure 4, we analyze the market effects of a mandate on the corn and fuel market

Figure 4. Equilibrium in the Corn and Ethanol Markets with a Binding Blend Mandate



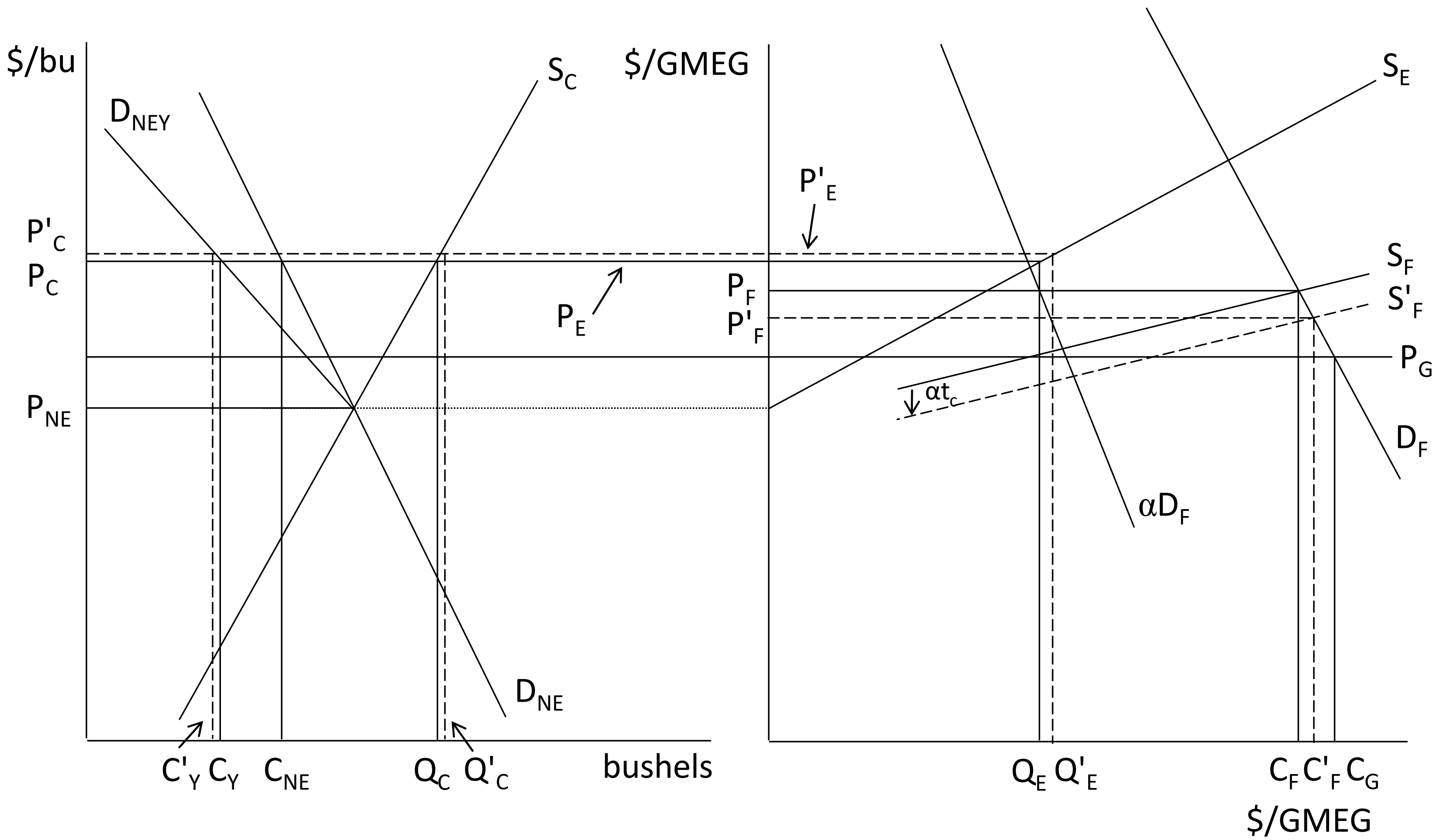
equilibria.[25] An exposition of the economics of a biofuel blend mandate is provided by de Gorter and Just (2009b). The purpose of Figure 4 is to explicitly show how the ethanol co-product recycling effect changes the ethanol market price (introducing the recycling effect is equivalent to assuming a flatter ethanol supply curve, S'_E in the first panel): the recycling effect reduces the price from P_E to P'_E. The recycling effect also decreases the corn market price. Compare this with the recycling effect's impact on ethanol and corn prices in Figure 1, where a blender's tax credit is the binding biofuel policy—in that situation, the recycling effect's flattening of the ethanol supply curve has no effect on ethanol or corn prices. Notice also that under the binding blend mandate, the ethanol market price coincides with the price received by ethanol producers. Even though the supply of yellow corn is decreased relative to a situation where the co-product is not considered ($Q'_C < Q_C$), the final quantity of ethanol is higher, $Q'_E > Q_E$. This occurs because of the co-product's recycling effect.

A Binding Biofuel Blend Mandate and a Tax Credit

In Figure 5, we show the impact of adding a blender's tax credit t_c to a binding blend mandate. A blender's tax credit is an ethanol consumption subsidy. It reduces the fuel price and increases the ethanol market price. This is shown in the second panel of Figure 5; the marginal cost of the final fuel blend S_F shifts down by an amount equal to the tax credit after adjusting for the share of ethanol in the fuel, αt_c. As a result, the pre-tax credit fuel price P_F decreases to P'_F and fuel consumption increases. Corresponding to increased fuel consumption is increased ethanol production. Because the ethanol supply curve is unaffected by the introduction of the tax credit, more ethanol will be produced only if the market price of ethanol increases from P_E to P'_E. The corn market price increases to P'_C following the increase in the ethanol price. However,

[25] In Figure 4, D_F, S_F and P_F denote the demand, supply and price of fuel (which is a blend of gasoline and ethanol); α denotes the percentage of ethanol in the blend.

Figure 5. Equilibrium in the Corn and Ethanol Markets with a Binding Blend Mandate and a Tax Credit



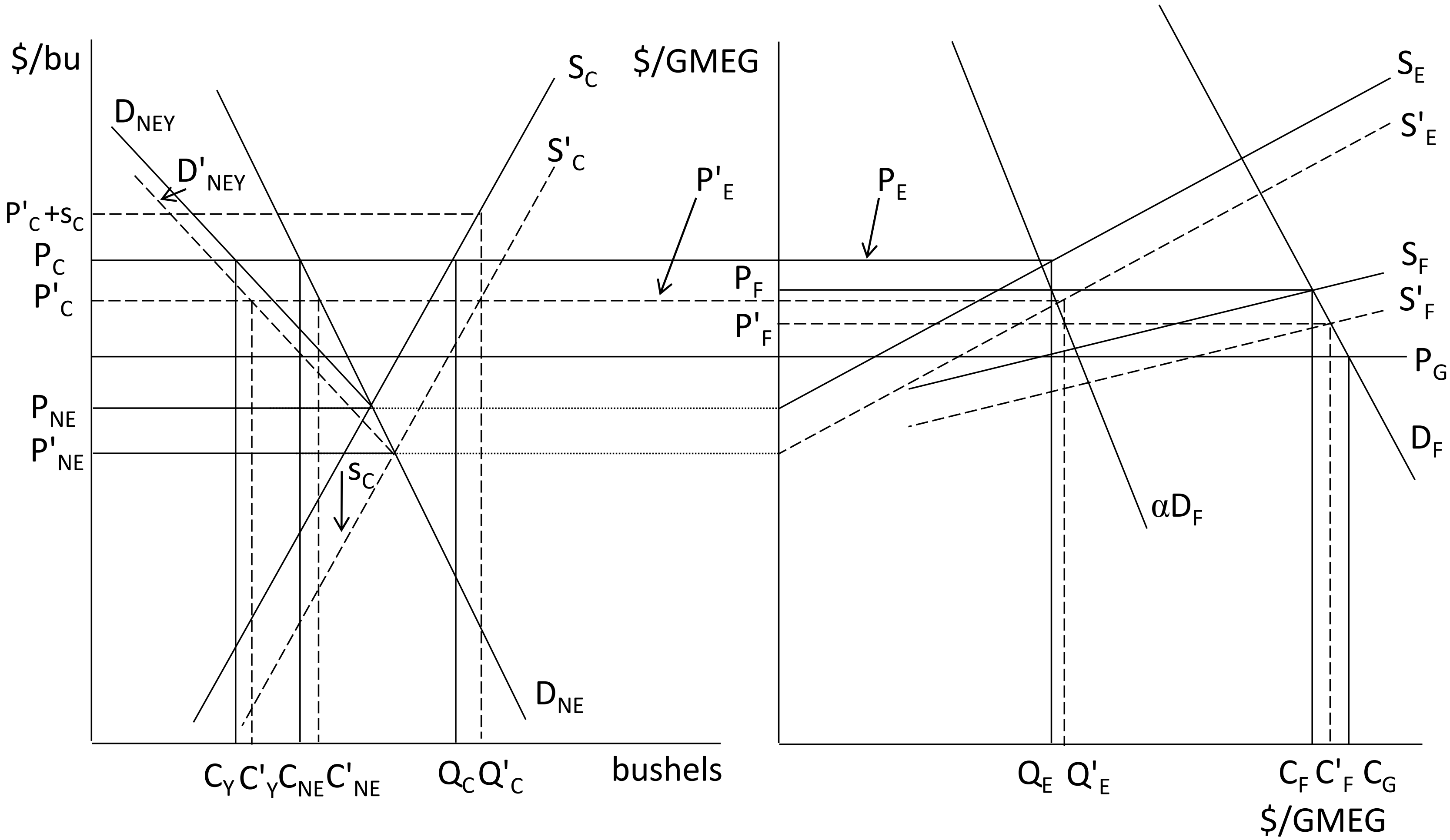
the corn price increase is likely to be small because demand for fuel is known to be inelastic and the ethanol supply curve is more elastic than shown here because of the recycling effect. Figure 5 also shows that addition of the tax credit to a binding blend mandate does not increase the ethanol price by the full amount of the tax credit. Therefore, the price premium due to the mandate and the tax credit are not additive – an argument previously made in de Gorter and Just (2009b).

A Binding Biofuel Blend Mandate and a Corn Production Subsidy

The effects of a corn production subsidy s_C on the corn supply curve and demand for non-ethanol yellow corn with a binding blend mandate, as shown in the first panel of Figure 6, are identical to the corn production subsidy's effects with a binding tax credit, as depicted in Figure 2. The corn production subsidy makes the ethanol supply curve shift to S'_E, which in turn decreases the marginal cost of the fuel blend supply to S'_F. The intersection of the new fuel supply curve with the fuel demand curve D_F constitutes a new equilibrium in the fuel market with a lower fuel price P'_F and higher fuel consumption C'_F. Thus, the corn production subsidy implicitly subsidizes fuel consumption. Since the quantities of fuel and ethanol are linked in equilibrium through the blend mandate, production of ethanol increases to Q'_E. The new ethanol market price P'_E corresponds to the new quantity of ethanol on the supply curve S'_E, and the price is decreased by the subsidy. Owing to the link between ethanol and corn prices, consumers of corn for non-ethanol use enjoy a lower market price P'_C, while corn producers receive the market price plus the subsidy.

The fuel market effects shown in the second panel of Figure 6 are similar but not identical to the effects in Figure 2 (where ethanol producers receive a lower market price and yet supply more). Without the subsidy, profits per bushel of corn to ethanol producers are

Figure 6. Equilibrium in the Corn and Ethanol Markets with a Binding Blend Mandate and a Corn Production Subsidy



$$\pi = \lambda\beta P_E - P_C + r\gamma P_C - \tilde{c}_0 \quad (10)$$

and with the corn production subsidy they are

$$\pi' = \lambda\beta P_E' - P_C' + r\gamma P_C' - \tilde{c}_0 \quad (11)$$

Hence, the effect of the corn production subsidy on ethanol producers' profits can be written as

$$\Delta\pi = \lambda\beta\left(P_E' - P_E\right) - \left(1 - r\gamma\right)\left(P_C' - P_C\right) \quad (12)$$

Because a production subsidy always lowers the market price of the subsidized product (corn, in this case), it must be the case that $P_C' - P_C < 0$. Assume for a moment that ethanol producers do not change their production of ethanol when the corn production subsidy is introduced. In this case, $P_E' = P_E$ and $\Delta\pi = -\left(1 - r\gamma\right)\left(P_C' - P_C\right) > 0$. Akin to the situation in Figure 2, positive economic profits and competition among ethanol producers must eventually result in increased ethanol production. However, because the derived demand of fuel blenders for ethanol, αD_F, has a negative slope, more ethanol will be blended only if the fuel price decreases. For the fuel price to decrease, the price of ethanol must decrease.[26] Ethanol producers will expand their production and the ethanol price will decrease until zero profits are made, or in terms of equation (12)

$$\Delta\pi = \underbrace{\lambda\beta\left(P_E' - P_E\right)}_{-} \underbrace{-\left(1 - r\gamma\right)\left(P_C' - P_C\right)}_{+} = 0 \quad (13)$$

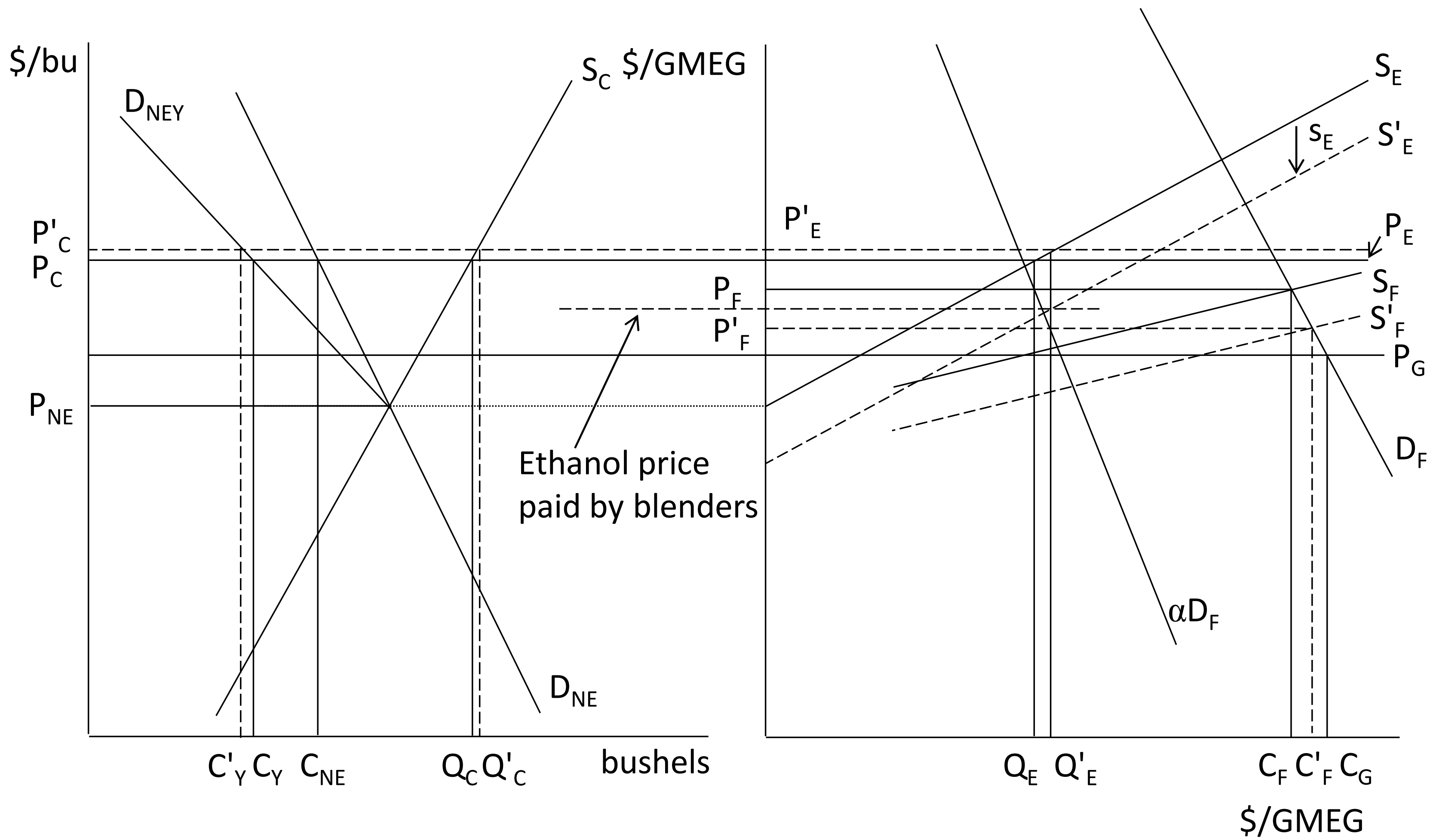
In the new equilibrium which is established, the negative term in equation (13) is exactly offset by the positive term.

A Binding Biofuel Blend Mandate and an Ethanol Production Subsidy

An ethanol production subsidy s_E lowers the marginal cost of ethanol production; this is represented as a shift in S_E to S'_E in the second panel of Figure 7. The production subsidy

[26] Recall that the fuel price is a weighted average of the ethanol and gasoline market prices. The weights are the shares of ethanol and gasoline, respectively, in the final fuel mix.

Figure 7. Equilibrium in the Corn and Ethanol Markets with a Binding Blend Mandate and an Ethanol Production Subsidy



decreases the market price of ethanol, making the fuel blend cheaper; this is depicted as a decrease in the marginal cost for blenders – a shift in S_F to S'_F. As a result, the fuel price decreases from P_F to P'_F, while fuel consumption increases from C_F to C'_F. In this respect, the ethanol production subsidy has the same effect as an ethanol blender's tax credit (a consumption subsidy). The market price of ethanol (paid by blenders) decreases, as shown by the intersection of S'_E with the quantity of ethanol supporting the market equilibrium at the fuel price P'_F. However, the ethanol price received by ethanol producers is equal to the market price of ethanol plus the production subsidy. The corn market price P'_C is therefore linked to P'_E. Notice that the price premium due to the blend mandate and the ethanol production subsidy are additive, unlike the case of the mandate combined with the tax credit. The increase in the corn price due to the corn production subsidy is likely to be small because of relatively inelastic demand for fuel and relatively elastic ethanol supply.

The comparative statics results for the binding blend mandate, which are presented in Table 4, are mostly identical to those for a binding tax credit. One important difference is that when the mandate binds, the tax credit, corn production subsidy and ethanol production subsidy increase the gasoline price. With a binding mandate, all of these policies implicitly subsidize fuel consumption, so they increase gasoline consumption and increase the gasoline price. An increase in the blend mandate always reduces the gasoline price because it is an implicit tax on gasoline, but the mandate's impacts on the market prices of fuel, ethanol, and corn are ambiguous. The ambiguous effect of a blend mandate on the fuel price has been well documented (de Gorter and Just 2009b; Lapan and Moschini 2009), but we are not aware of any previous work which shows that the mandate's effect on the ethanol price is also ambiguous. Intuitively (although not completely technically correct), because the mandate can either increase or decrease the fuel price, it can also increase or decrease the equilibrium fuel quantity. But because the quantity of ethanol is linked to the quantity of fuel through the blend mandate, the ethanol quantity effect can be either positive or negative. If the ethanol quantity decreases, the ethanol price also decreases.

Table 4. Comparative Statics Results for a Binding Blend Mandate

		Effect on			
		P_G	P_E	P_F	P_C
Change in	t_c	+	+	–	+
	s_C	+	–	–	–
	s_E	+	–	–	+
	α	–	+/–	+/–	+/–

Source: Appendix 2

5. Revisiting the Concept of 'Water' in a Biofuel Policy

Consider a situation where ethanol consumption is not mandated but instead an ethanol consumption subsidy (either a blender's tax credit or a tax exemption) is provided to incentivize consumers to purchase the biofuel. Consistent with the previous literature (e.g., de Gorter and Just 2008, 2009a; Holland et al. 2009; Lapan and Moschini 2009; Cui et al. 2011; Chen et al. 2011), we assume that do not demand the fuel *per se*, but rather they demand vehicle-miles-traveled which the fuel produces for final consumers. Therefore, if we assume that consumers have a choice between gasoline and ethanol, and a gallon of ethanol provides 70 percent of the vehicle-miles-traveled provided by a gallon of gasoline, they will be willing to pay for one gallon of ethanol only 70 percent of the price at which they can purchase one gallon of gasoline. We also assume that blenders view ethanol and gasoline as perfect substitutes. Therefore, they will be indifferent between the two fuels only if the price per mile is equalized; this is how equation (5) is derived. In the analysis to follow, we consider an endogenous gasoline price.

Since equation (5) determines the ethanol market price with a binding blender's tax credit, and because it assumes the tax credit is the only biofuel policy, by setting the tax credit equal to zero we can obtain a hypothetical ethanol market price P_E^* that would render consumers indifferent between ethanol and gasoline without any biofuel policy

$$P_E^* = P_G^* - \left(\frac{1}{\lambda} - 1\right)t \tag{14}$$

The term P_G^* in equation (14) denotes the gasoline price that would exist in the fuel market in the absence of biofuel policies; notably, if no ethanol were produced, then P_G^* would be determined by the intersection of the demand and supply curves for gasoline (or excess demand and supply curves under international trade). Note that since $P_E^* < P_G^*$, ethanol production is unlikely to occur at P_G^* because the intercept of the ethanol supply curve has historically been above the gasoline market price. However, if the gasoline price were high enough, ethanol production would occur without any policy intervention. The hypothetical ethanol market price P_E^* does not depend on any biofuel policy; therefore, it can be used to compare market effects of various biofuel policies. Notice also that owing to the absence of the tax credit, the hypothetical no-policy ethanol price can be relatively low.

The concept of 'water' in a biofuel policy arises from two prices already discussed: the intercept of the ethanol supply curve, P_{NE}, and the hypothetical gasoline energy-equivalent ethanol market price P_E^*. Intuitively, if P_{NE} is greater than P_E^*, then part of the corn price increase caused by a biofuel policy will have no actual effect on market outcomes; until the corn price increases enough to fill the gap between P_{NE} and P_E^*, no biofuel is actually produced. The gap between P_{NE} and P_E^* is referred to as 'water' in the biofuel price premium. This means, within the range of water, a biofuel policy has no effect on corn prices. Intuitively, 'water' can be thought of as representing the waste of societal resources that occurs when production of ethanol is incentivized through biofuel policies despite it costing more than gasoline to produce.

In defining the 'water' in a biofuel policy price premium, the previous literature (de Gorter and Just 2008, 2009a) does not take into account the penalty due to the volumetric fuel tax.[27] They define water w as the difference between the intercept of the ethanol supply curve corresponding to the non-ethanol corn price P_{NE} and the blenders' gasoline (oil) price P_{Gb} (expressed in dollars per bushel) under a biofuel policy

$$w = P_{NE} - P_{Gb} = P_{NE} - \frac{\lambda\beta}{1-r\gamma}\left(P_G - c_0\right) \tag{15}$$

In reality, the fuel tax represents a significant share of the gasoline price (even more so in the European Union than in the United States); ignoring the presence of a volumetric fuel tax will bias our estimate of water and the rectangular deadweight cost of a biofuel policy) significantly. To illustrate the concepts, we take the tax credit as an example. The logic outlined below also holds for a binding biofuel mandate and any combination of biofuel policies.

Assume that no biofuel policy exists in Figure 1. Corresponding to this situation is an ethanol price P_E^* defined by equation (14).[28] Consider a sufficiently large tax credit t_c that increases the ethanol market price to P_E, where P_E is defined by equation (5). Recalling that 'water' is the range of ethanol prices where a biofuel policy has no impact on the corn price, we

[27] In this respect, the previous literature describes 'water' in the special case of a zero fuel tax.
[28] The price of gasoline is depicted below the intercept of the ethanol supply curve in Figure 1 only. In other figures, the price of gasoline is above P_{NE} and hence, we do not depict 'water'. This does not affect our graphical analyses of the other figures.

can depict 'water' in Figure 1 as the difference between the intercept of the ethanol supply curve P_{NE} (in dollars per GMEG) and P_E^* [29]

$$w = P_{NE}^{GMEG} - P_E^* = P_{NE}^{GMEG} - \left[P_G^* - \left(\frac{1}{\lambda} - 1 \right) t \right] \tag{16}$$

'Water' is also equal to the distance *ci* in the second panel of Figure 1. This distance is always greater than (or equal to) the distance *cg*, which corresponds to the 'water' as originally defined by de Gorter and Just (2008, 2009a). Since de Gorter and Just relate water to the endogenous gasoline price rather than P_E^*, they ignore the role of the volumetric fuel tax. The penalty to fuel blenders due to the volumetric fuel tax is represented by the distance *ei*, and it corresponds to the second (negative) term on the right-hand side of equation (14).

The *price premium* of a biofuel policy is defined as the difference between the producer price of ethanol (which is equal to its production cost) and the hypothetical gasoline-equivalent ethanol price P_E^*. Since the gasoline-equivalent ethanol price is biofuel policy-invariant, the price premium is only affected by a change in the ethanol producer price. Note that if an ethanol production subsidy is present, it generates two unique effects, unlike other policies analyzed: the ethanol market price decreases (perhaps only marginally), and the corn price (which is linked to the ethanol producer price) increases.

It follows from Figure 1 that with an endogenous gasoline price, the price premium due to a blenders' tax credit is always less than the tax credit itself. The price premium must be smaller because the tax credit causes the gasoline (oil) price to decrease, which moderates the tax credit's effect on the ethanol price. In contrast, if the gasoline price did not decrease, the ethanol

[29] Because the prices and quantities of corn and ethanol are linked through equations (2) and (6), respectively, the amount of water in either market is the same, up to measurement units. We measure water in the fuel market.

price would be above P_E in the second panel of Figure 1. The ethanol price premium equals the tax credit only if the gasoline price is exogenous.

Explicitly embedded in equation (14) is the fact that the fuel market is distorted by the volumetric fuel tax: consumers are willing to pay a price for fuel (inclusive of the tax) according to the mileage the fuel produces, but blenders are taxed on fuel by volume. To attain a distortion-free economy, a tax credit equal to the penalty due to the volumetric fuel tax would be required[30]

$$\hat{t}_c = \left(\frac{1}{\lambda} - 1\right)t \qquad (17)$$

It could be argued that 'water' should be calculated with respect to a distortion-free price of ethanol which equals the price of gasoline when expressed in dollars per GMEG. However, calculating 'water' using this ethanol price and the de Gorter and Just formula in (15) above is equivalent to calculating 'water' using equation (16) above, which incorporates the penalty to fuel blenders as a separate term. Whether we adjust the tax credit to reflect the volume-energy disparity between ethanol and gasoline or we adjust the calculation of 'water' directly, we will obtain the same value for 'water' which captures the difference between ethanol and gasoline costs to society.

Closely related to the concept of 'water' in the biofuel price premium are the 'rectangular' deadweight costs (DWC) associated with the biofuel policy. Rectangular DWC represent a pure welfare loss—a transfer of resources that does not benefit anyone. Consider the second panel of Figure 1: area *abkl* represents the taxpayers' cost of the tax credit that gets transferred to corn producers, area *abcd*, and domestic fuel consumers (and foreign oil consumers but that is accounted for in the terms of trade effect), area *efgh*. The area that is not attributable to anyone is equal to *cdef* + *ghkl* and represents the rectangular DWC of the

[30] This tax credit can be thought of as a Pigovian subsidy.

blenders' tax credit. Notice that area *cdij*, which represents the waste of resources associated with 'water', is equal to *cdef* + *ghkl*.[31] This means that the rectangular DWC can be calculated as the level of 'water' multiplied by the quantity of ethanol produced. This method of rectangular DWC calculation holds for any biofuel policy.

The preceding analysis has assumed that consumers can buy a fuel with any share of ethanol as long as the price per mile traveled is equalized between ethanol and gasoline. In reality, however, this assumption is mostly not met, because currently most gas stations offer premixed blends of fuel containing 10, 15, or 85 percent ethanol. Blenders are essentially "watering down the scotch" by adding ethanol to the fuel blend. Consumers of the fuel blend face a *de facto* mandate, because they want to buy fuel according to miles but are not able to. Moreover this mandate exists even if the actual share of ethanol in the total fuel is greater than a specified blend mandate. The difference between the observed ethanol market price and the hypothetical price represents a price premium due to no choice of fuel.

We have described so far how ethanol production could arise solely because of a biofuel policy and how a biofuel policy could be in place but not be binding. A third market equilibrium could also arise where there is no biofuel policy in place but ethanol is still consumed. For example, this equilibrium obtained in 2006 after the ban of MTBE, a low-cost alternative to ethanol. This is also a *de facto* mandate because ethanol is consumed in a certain proportion to gasoline when it is used as an oxygenator and octane enhancer. This proportion is typically lower than the blend mandate levels which have prevailed under U.S. policy. It could therefore be argued that the ethanol market price under this scenario should be the no-policy counterfactual, rather than the hypothetical gasoline-equivalent price defined by equation (14). In this case, our definition of 'water' represents an upper bound on the true level of 'water' in the blend mandate.

[31] Figure 1 is not drawn to scale. This equality follows from the equations defining P_E and P_E^*.

However, it could be the case that ethanol for oxygenator and octane enhancer purposes would be produced from sugar cane in Brazil rather than from corn in the U.S., in the absence of U.S. biofuel policies. During the past decades, sugar-cane ethanol from Brazil has been less expensive in the U.S. than corn ethanol, even taking into account transportation costs to the U.S. This suggests that the U.S. ethanol import tariffs (equal to about 58 percent) would have been an important driver in influencing corn prices in the past, had there not been any other ethanol policy in place.

6. An Empirical Illustration

For each year between 2008 and 2011, inclusive, we calibrate the model of the corn and fuel markets in the U.S. described above, using the data and parameters detailed in Appendix 4.[32] We calibrate each year's model to four simultaneous biofuel policies: a binding blend mandate combined with a blenders' tax credit, an ethanol production subsidy and a corn production subsidy. We assume that the supply and demand curves in all markets exhibit constant price elasticities. The U.S. corn production supplies domestic demand for yellow corn and export demand, as well as demand for corn to be used in ethanol production. The U.S. is an importer of gasoline and is assumed to consume its entire production of ethanol; the rest of the world is assumed to consume only gasoline. Using the calibrated model, we simulate various combinations of the four biofuel policies.

Table 5 provides an overview of the observed gasoline and ethanol market prices – P_G and P_E, respectively – as well as their hypothetical counterparts, P_G^* and P_E^*, which would prevail in the fuel market if no biofuel policies were in place.

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[32] All models are calibrated to the observed market prices and quantities, with the assumption that the blend mandate determines the ethanol market price. This assumption is likely to be violated in the recent period, however, because the ethanol market price seems to have been determined outside of the United States since the end of 2010; hence, the U.S. mandate is dormant (i.e., does not determine the market price). The violation of this assumption does not affect our major conclusions because most of our results are derived directly from the observed data.

Table 5. Gasoline and Ethanol Prices

	2008	2009	2010	2011
Observed gasoline price P_G ($/gal)	2.57	1.76	2.17	2.90
Hypothetical gasoline price (no ethanol) P_G* ($/gal)	2.64	1.81	2.24	3.00
Observed ethanol price P_E ($/gal)	2.47	1.79	1.93	2.70
Hypothetical ethanol price (no biofuel policy) P_E* ($/gal)	1.70	1.12	1.42	1.96
Observed ethanol price P_E ($/GMEG)	3.53	2.56	2.76	3.86
Hypothetical ethanol price (no biofuel policy) P_E* ($/GMEG)	2.42	1.60	2.03	2.80
Hypothetical ethanol price as % of observed ethanol price	69	63	74	72
Hypothetical ethanol price as % of hypothetical gasoline price	92	88	91	93

Source: caluclated

For convenience, gasoline and ethanol prices are expressed in dollars per gallon (that is, we do not adjust the ethanol price for mileage). The hypothetical gasoline prices are always greater than the observed prices; the difference ranges between two and four percent. This occurs because existing biofuel policies effectively impose a tax on gasoline producers, resulting in a lower gasoline price relative to a no policy counterfactual. This suggests that although recent biofuel policies do have an impact on world gasoline prices, this effect is not very significant – in terms of price – owing to a small share of ethanol in total world fuel consumption.[33] However, it should come as no surprise that even a small change in the gasoline price can result in sizable monetary effects because of the large quantity of gasoline that is consumed.

The hypothetical ethanol market prices are significantly less than the observed ethanol prices; the hypothetical gasoline-equivalent ethanol price is about 70 percent of the observed ethanol price over the analyzed period (its fraction is smallest in 2009 at 63 percent). The hypothetical prices are less than the observed ones because, unlike the observed prices, they do not include the blender's tax credit. Note that the hypothetical ethanol price P_E^* is significantly

[33] In reality, however, biofuel policies are likely to have a stronger reduction effect on the world gasoline price because the United States is not the only ethanol producer; this is in contrast to our simplifying assumption in the paper.

below the hypothetical gasoline price P_G^* because of the fuel tax; the difference is equal to 0.43×*fuel tax.*

In Table 6, we present key corn and ethanol prices expressed in dollars per bushel over the period 2008 -2011. Not surprisingly, corn prices are the highest in 2008 and 2011, that is, years that saw spikes in food commodity prices. The intercept of the ethanol supply curve corresponds to the intersection of the corn supply curve and the total demand curve for non-ethanol corn. The intercept value varies over time, reaching peaks in 2008 ($3.59/bu) and 2011 ($4.11/bu).

Table 6. Ethanol Price Premium due to All Four Policies ($/bushel)†

	2008	2009	2010	2011
Observed corn price P_C	4.78	3.75	3.83	6.01
Non-ethanol corn price P_{NE}	3.59	2.70	2.67	4.11
Hypothetical ('no-policy') ethanol price P^*_E	1.27	0.69	1.34	2.55
Ethanol price premium = P_C - P^*_E	3.51	3.06	2.49	3.47
Net change in corn price $\Delta P_C = P_C - P_{NE}$	1.19	1.04	1.16	1.91

Source: calculated

Note: † The four policies are: blender's tax credit, blend mandate, ethanol production subsidy, corn production subsidy.

Although the peaks coincide with the years when commodity prices spiked, it is not necessarily the case that the observed commodity price spikes were caused only by shifts (shocks) in corn demand or supply. For example, when the tax credit determines the ethanol price (and the oil supply is perfectly elastic), any shock in the corn market actually has no effect on the corn price unless the resulting change in ethanol production affects the oil price. The third row of Table 6 presents the hypothetical ethanol market price expressed in dollars per bushel (a counterpart to Table 5).

The ethanol policy price premium (measured in dollars per bushel) in Table 6 is obtained by subtracting the values in the third row from those in the first row. [34] There are at least four reasons why the ethanol price premium of the combination of the existing biofuel policies is so high. First, the blend mandate is binding (by assumption). Second, consumers have a limited choice of fuel blends because there are few E-85/E-15 retail outlets; this imposes a *de facto* mandate in which the actual blend is greater than the mandated one. Third, the MTBE ban and Clear Air Act also constitute a *de facto* mandate, and the import tariff on sugar-cane ethanol supports it. Fourth, the world ethanol price may be determined outside of the United States (as it seems to have been the case since the end of 2010); if the world price exceeds the ethanol price which the U.S. biofuel policies would generate, then the price premium which results is even greater than it would be with the mandate alone (de Gorter et al. 2011).

Finally, in the last row of Table 6 we report the effect on the corn market price which can be attributed to the existing biofuel policies. These values are obtained by taking the difference between the observed corn price and the intercept of the ethanol supply curve (in dollars per bushel).[35] In absolute terms, the biofuel policies have the greatest effect on corn prices in 2008 and 2011, although the 2011 effect is more than 60 percent greater than the 2008 effect.

In Table 7, we provide a breakdown of how individual biofuel policies change the corn price relative to a no-policy scenario (P_{NE}) in which the corn price is determined by the intersection of the corn supply curve and demand for non-ethanol corn. If the corn price is below P_{NE} (because of 'water'), then no ethanol production would have occurred in that year. This seems to be the case in 2008 and 2009, as the first line of Table 7 documents. For example,

[34] As explained above, the presence of biofuel policies reduces the gasoline price, and if this price were used to compute the hypothetical ethanol price, then the price premium would increase.
[35] The price P_{NE} is simulated. It is the corn price that equilibrates the U.S. corn supply with the sum of the domestic and export demand for yellow corn under no ethanol production.

Table 7. Estimated Change in the Corn Price due to Different Policies

	Change in the corn price relative to a no policy scenario							
	2008		2009		2010		2011	
	$/bu	% change	$/bu	% change	$/bu	% change	$/bu	% change
Tax credit	-0.18	-5.0	-0.13	-4.8	0.49	18.4	0.33	8.1
Mandate	1.26	35.1	1.10	40.8	1.21	45.3	1.96	47.7
Mandate differential	**1.44**	**40.0**	**1.23**	**45.6**	**0.72**	26.8	**1.63**	**39.6**
Tax credit & ethanol production subsidy	0.31	8.6	0.35	12.9	0.96	36.1	0.81	19.7
Mandate & ethanol production subsidy	1.26	35.1	1.11	40.9	1.21	45.3	1.96	47.7
Mandate differential	**0.95**	**26.5**	**0.76**	**28.0**	**0.25**	9.3	**1.15**	**28.1**
Tax credit & corn production subsidy	-0.18	-5.0	-0.13	-4.8	0.49	18.2	0.33	7.9
Mandate & corn production subsidy	1.18	32.8	1.04	38.4	1.15	43.1	1.90	46.2
Mandate differential	**1.36**	**37.8**	**1.16**	**43.1**	**0.67**	24.9	**1.57**	**38.3**
Tax credit & ethanol production subsidy & corn production subsidy	0.30	8.4	0.34	12.7	0.96	35.8	0.80	19.5
Mandate & ethanol production subsidy & corn production subsidy	1.18	32.9	1.04	38.4	1.15	43.2	1.90	46.2
Mandate differential	**0.88**	**24.5**	**0.69**	**25.7**	**0.20**	7.3	**1.10**	**26.7**
Mandate & tax credit & ethanol production subsidy & corn production subsidy	1.19	33.0	1.04	38.6	1.16	43.4	1.91	46.5

Note: The discrepancies are due to rounding errors.

Source: calculated

because the per-bushel-of-corn equivalent of the 2008 55.8¢/gal blenders' tax credit is \$2.14/bu and the 'water' associated with the tax credit alone is \$2.32/bu (not reported), the net effect of the introduction of the tax credit on corn prices is negative ¢18/bu. On the other hand, the mandate alone would increase corn prices above their baseline values by \$1/bu – \$2/bu, depending on the year. In other words, the mandate increases corn prices by \$0.72/bu – \$1.63/bu more than the tax credit does (this is denoted as the 'mandate differential' in Table 7). If one adds the ethanol production subsidies, this differential declines to \$0.25/bu – \$1.15/bu; the differential decreases even more, to \$0.20/bu – \$1.10/bu, if both corn and ethanol production subsidies are added to the tax credit or mandate. The final row in Table 7 shows that corn prices increase by \$1.04/bu – \$1.91/bu with the corn production subsidy and the three ethanol policies combined (the actual policy case), which corresponds to a 33 – 46.5 percent increase in the corn price.

Table 8 presents estimates of rectangular deadweight costs for the observed baseline (all four policies combined) in the years 2008 – 2011. For example, the values in the first row suggest that the rectangular deadweight costs totaled 21.3 billion dollars (in nominal terms) over the four years analyzed. The deadweight loss due to the volume/miles penalty constitutes a significant share of the total rectangular deadweight costs – between 25 and 43 percent, depending on the year. The rectangular DWC represent approximately ten percent of the value of corn production between 2008 and 2011.

Table 8. Estimates of Rectangular Deadweight Costs for the Observed Baseline (All Four Policies)

	2008	2009	2010	2011
Rectangular DWC (bil. $)	5.84	5.87	4.44	5.15
% of DWC due to penalty	24.50	27.64	42.42	36.85
% of rectangular DWC in value of corn production	9.69	11.47	8.55	6.57

Source: calculated

Note: DWC - Deadweight costs

The four policies are: blender's tax credit, blend mandate, ethanol production subsidy, corn production subsidy.

7. Conclusions

This paper has developed a framework to analyze the market effects of biofuel mandates, consumption subsidies (U.S. blender's tax credit or EU tax exemption) and production subsidies for ethanol or corn. We have focused on the impact of these policies on corn and ethanol prices. By properly taking into account the market effects of the ethanol co-product, we conclude that the ethanol supply curve is more elastic than previously thought, because the co-product's existence makes more yellow corn available to ethanol producers (at any corn price above the intercept of the ethanol supply curve).

We determined a hypothetical ethanol market price that would make consumers indifferent between purchasing gasoline or ethanol if there were no biofuel policies and consumers demanded fuel according to its mileage. This 'no policy' ethanol market price has important implications for 'water' (the gap between the intercept of the ethanol supply curve and the hypothetical ethanol price) associated with a biofuel policy because this price is much lower than the gasoline price, and the gasoline price has been used to calculate 'water' in the previous literature. Thus, our results show that the rectangular deadweight costs associated with 'water' were underestimated in the previous literature. We also analyzed the unique interaction effects between mandates and tax credits and included ethanol and corn production subsidies. All these issues have major implications for the market effects of ethanol policies, particularly on the level of corn prices.

We found that the ethanol price premium is very high; for example, in 2008 it is estimated to be \$3.51/bu, which represents 83 percent of the ethanol market price. However, the impact of the price premium due to biofuel policies on corn market prices, although still significant, is tempered by the existence of 'water'.

It is to be noted that the level of ‘water’, apart from the hypothetical ethanol price, significantly depends on the non-ethanol corn price, that is, the price that would clear the corn market if no ethanol were produced. The non-ethanol corn price is affected, among other factors, by U.S. biofuel policies aimed at non-corn ethanol biofuels (such as biodiesel or cellulosic ethanol) and by biofuel policies in the rest of the world. The former effect occurs because of competition for agricultural land which increases the marginal cost to corn producers, shifts the corn supply curve up, and thus increases the non-ethanol corn price. The latter effect is reflected in demand for U.S. yellow corn exports. Because biofuel policies in the rest of the world increase the export demand for yellow corn facing the United States, they increase the non-ethanol corn price. Hence, the impact of U.S. biofuel policies on corn prices would have been larger if there had been no biofuel policies in the rest of the world.

Appendix 1. Model with an Endogenous Gasoline Price and a Binding Tax Credit

For analytical tractability, we present a model for a closed economy, assuming a zero fuel tax. All quantities are expressed in gasoline miles equivalent gallons (GMEGs). Ethanol and gasoline are assumed to be perfect substitutes, and consumers can choose which fuel to purchase. They value the fuel for miles traveled. Consumers are willing to buy ethanol if the price of the fuel blend (gasoline and ethanol) P_F equals the price of gasoline P_G; the latter must equal the ethanol market price P_E less the blender's tax credit t_c

$$P_F = P_G = P_E - t_c \tag{A1.1}$$

The corn market price P_C is linked to the ethanol market price, the ethanol production subsidy s_E and the ethanol processing cost c_0

$$P_C = \frac{\lambda\beta}{1-r\gamma}\left(P_E + s_E - c_0\right) \tag{A1.2}$$

where λ denotes miles traveled per gallon of ethanol relative to gasoline; β is the number of gallons of ethanol produced from one bushel of corn; r denotes the relative price of the ethanol co-product (DDGS) and corn; and γ denotes the share of corn that gets returned back to the market as the co-product.

The equilibrium condition for the fuel market is given by

$$S_G\left(P_G\right) + S_E\left(P_E + s_E\right) = D_F\left(P_F\right) \tag{A1.3}$$

where S_G, S_E and D_F denote gasoline supply, ethanol supply and fuel demand, respectively.

Finally, ethanol supply $S_E\left(P_E + s_E\right)$ is defined by the identity

$$S_E\left(P_E + s_E\right) \equiv \frac{\lambda\beta}{1-r\gamma}\left[S_C\left(P_C + s_C\right) - D_{NE}\left(P_C\right)\right] \tag{A1.4}$$

where S_C denotes corn supply, D_{NE} is non-ethanol corn demand (inclusive of any co-product) and s_C denotes a corn production subsidy.

Totally differentiating the system of equations (A1.1 – A1.4) and solving, we obtain

$$\frac{dP_F}{dt_c} = \frac{dP_G}{dt_c} = -\frac{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2 \left[S_C'(P_C + s_C) - D_{NE}'\right]}{A} < 0, > -1$$

$$\frac{dP_E}{dt_c} = \frac{S_G' - D_F'}{A} > 0, < 1 \tag{A1.5}$$

$$\frac{dP_C}{dt_c} = \frac{\frac{\lambda\beta}{1-r\gamma}\left(S_G' - D_F'\right)}{A} > 0$$

where $A = S_G' - D_F' + \left(\frac{\lambda\beta}{1-r\gamma}\right)^2 \left[S_C'(P_C + s_C) - D_{NE}'\right] > 0$

$$\frac{dP_F}{ds_E} = \frac{dP_G}{ds_E} = \frac{dP_E}{ds_E} = -\frac{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2 \left[S_C'(P_C + s_C) - D_{NE}'\right]}{A} < 0, > -1$$

$$\frac{dP_C}{ds_E} = \frac{\frac{\lambda\beta}{1-r\gamma}\left(S_G' - D_F'\right)}{A} > 0 \tag{A1.6}$$

$$\frac{dP_F}{ds_C} = \frac{dP_G}{ds_C} = \frac{dP_E}{ds_C} = -\frac{\frac{\lambda\beta}{1-r\gamma} S_C'(P_C + s_C)}{A} < 0$$

$$\frac{dP_C}{ds_C} = -\frac{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2 S_C'(P_C + s_C)}{A} < 0 \tag{A1.7}$$

The set of derivatives (A1.5) reveals that if the tax credit is the binding biofuel policy, then an increase in the tax credit reduces the gasoline and fuel prices but increases the corn and ethanol market prices. An increase in the ethanol production subsidy reduces the market price of fuel, gasoline and ethanol by the same amount, and it increases the market price of corn (derivatives (A1.6)). The last set of derivatives (A1.7) shows that the prices of fuel, gasoline and ethanol decrease by the same amount with an increase in the corn production subsidy; unlike with an ethanol production subsidy, a corn production subsidy always reduces the corn market price. The tax credit and the ethanol production subsidy have the same effect on the corn price.

Combining the derivatives from (A1.6) and (A1.7) yields

$$\left| \frac{dP_C}{ds_C} \Big/ \frac{dP_C}{ds_E} \right| = \frac{\frac{\lambda\beta}{1-r\gamma} S_C'\left(P_C + s_C\right)}{S_G' - D_F'} = \frac{\frac{\eta_{SC} S_C}{\left(P_C + s_C\right)} \frac{\lambda\beta}{\left(1-r\gamma\right)}}{\eta_{SG} \frac{S_G}{P_G} - \eta_{DF} \frac{D_F}{P_G}} \tag{A1.8}$$

This means that the probability that a corn production subsidy has a greater effect on the corn market price than an equivalent ethanol production subsidy increases as the corn supply becomes more elastic and gasoline supply and demand become less elastic. The same holds for a comparison of the corn production subsidy and the tax credit.

Similarly, the probability that a tax credit has a greater effect on the ethanol market price than an ethanol production subsidy increases as the gasoline supply and demand become more elastic and the corn supply and demand become more inelastic

$$\left| \frac{dP_E}{dt_c} \Big/ \frac{dP_E}{ds_E} \right| = \frac{S_G' - D_F'}{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2 \left[S_C'\left(P_C + s_C\right) - D_{NE}'\right]} = \frac{\eta_{SG} \frac{S_G}{P_G} - \eta_{DF} \frac{D_F}{P_G}}{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2 \left[\eta_{SC} \frac{S_C}{\left(P_C + s_C\right)} - \eta_{DNE} \frac{D_{NE}}{P_C}\right]} \tag{A1.9}$$

Finally, the tax credit and the ethanol production subsidy have the same effect on gasoline and fuel prices.

Appendix 2. Model with an Endogenous Gasoline Price and a Binding Blend Mandate

The model considers a blend mandate, tax credit, ethanol production subsidy and corn production subsidy. The blend mandate is assumed to be binding, that is, it determines the ethanol market price. The first three equations are the same as in Appendix 1

$$P_C = \frac{\lambda\beta}{1-r\gamma}\left(P_E + s_E - c_0\right) \tag{A2.1}$$

$$S_G\left(P_G\right) + S_E\left(P_E + s_E\right) = D_F\left(P_F\right) \tag{A2.2}$$

$$S_E\left(P_E + s_E\right) \equiv \frac{\lambda\beta}{1-r\gamma}\left[S_C\left(P_C + s_C\right) - D_{NE}\left(P_C\right)\right] \tag{A2.3}$$

With a blend mandate α equal to the share of ethanol in the final fuel blend, the fuel price is equal to a weighted average of ethanol and gasoline prices; the weights are equal to α and (1-α), respectively

$$P_F = \alpha\left(P_E - t_c\right) + \left(1-\alpha\right)P_G \tag{A2.4}$$

Ethanol supply must also satisfy

$$S_E\left(P_E + s_E\right) = \alpha D_F\left(P_F\right) \tag{A2.5}$$

Totally differentiating the system of equations (A2.1 – A2.5) and solving for the desired derivatives, we obtain

$$\frac{dP_F}{d\alpha}=\frac{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(\left(P_E-t_c-P_G\right)S_G'-\left(1-\alpha\right)D_F\right)+\alpha S_G'D_F}{B}$$

$$\frac{dP_G}{d\alpha}=\frac{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(\left(1-\alpha\right)\left(P_E-t_c-P_G\right)D_F'-D_F\right)+\alpha D_F D_F'}{B}<0 \quad \text{(A2.6)}$$

$$\frac{dP_E}{d\alpha}=\frac{\left(S_G'-\left(1-\alpha\right)D_F'\right)D_F+\alpha\left(P_E-t_c-P_G\right)S_G'D_F'}{B}$$

$$\frac{dP_C}{d\alpha}=\frac{\frac{\lambda\beta}{1-r\gamma}\left(\left(S_G'-\left(1-\alpha\right)D_F'\right)D_F+\alpha\left(P_E-t_c-P_G\right)S_G'D_F'\right)}{B}$$

where $B=\left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2D_F'\right)-\alpha^2S_G'D_F'>0$

$$\frac{dP_F}{dt_c}=-\frac{\alpha\left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]S_G'}{B}<0$$

$$\frac{dP_G}{dt_c}=-\frac{\alpha\left(1-\alpha\right)\left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]D_F'}{B}>0 \quad \text{(A2.7)}$$

$$\frac{dP_E}{dt_c}=-\frac{\alpha^2S_G'D_F'}{B}>0,<1$$

$$\frac{dP_C}{dt_c}=-\frac{\alpha^2\frac{\lambda\beta}{1-r\gamma}S_G'D_F'}{B}>0$$

$$\frac{dP_F}{ds_E} = -\frac{\alpha\left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left[S_C'(P_C+s_C)-D_{NE}'\right]S_G'}{B} < 0$$

$$\frac{dP_G}{ds_E} = -\frac{\alpha(1-\alpha)\left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left[S_C'(P_C+s_C)-D_{NE}'\right]D_F'}{B} < 0$$

$$\frac{dP_E}{ds_E} = -\frac{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left[S_C'(P_C+s_C)-D_{NE}'\right]\left(S_G'-(1-\alpha)^2 D_F'\right)}{B} < 0, > -1 \qquad \text{(A2.8)}$$

$$\frac{dP_C}{ds_E} = -\frac{\alpha^2\frac{\lambda\beta}{1-r\gamma}S_G'D_F'}{B} > 0$$

$$\frac{dP_F}{ds_C} = -\frac{\alpha\frac{\lambda\beta}{1-r\gamma}S_C'(P_C+s_C)S_G'}{B} < 0$$

$$\frac{dP_G}{ds_C} = -\frac{\alpha(1-\alpha)\frac{\lambda\beta}{1-r\gamma}S_C'(P_C+s_C)D_F'}{B} > 0$$

$$\frac{dP_E}{ds_C} = -\frac{\frac{\lambda\beta}{1-r\gamma}S_C'(P_C+s_C)\left(S_G'-(1-\alpha)^2 D_F'\right)}{B} < 0 \qquad \text{(A2.9)}$$

$$\frac{dP_C}{ds_C} = -\frac{\left(\frac{\lambda\beta}{1-r\gamma}\right)^2 S_C'(P_C+s_C)\left(S_G'-(1-\alpha)^2 D_F'\right)}{B} < 0$$

Appendix 3. Elasticity of the Ethanol Supply Curve

Following Figure 1, the ethanol supply curve can be written as

$$S_E\left(P_E\right) \equiv \frac{\lambda\beta}{1-r\gamma}\left(S_C\left(P_C\right) - D_D\left(P_C\right) - D_X\left(P_C\right)\right) \tag{A3.1}$$

where the right-hand side denotes the difference between the domestic corn supply S_C and domestic non-ethanol corn demand D_D and foreign export demand D_X (both inclusive of the ethanol co-product). Note that identity (A3.1) is an extended version of equation (6).

Totally differentiating and rearranging identity (A3.1), we obtain

$$\frac{dS_E}{dP_E} = \frac{\lambda\beta}{1-r\gamma}\left(\frac{dS_C}{dP_C} - \frac{dD_D}{dP_C} - \frac{dD_X}{dP_C}\right)\frac{dP_C}{dP_E} \tag{A3.2}$$

The link between ethanol and corn prices implies

$$\frac{dP_C}{dP_E} = \frac{\lambda\beta}{1-r\gamma} \tag{A3.3}$$

which, when substituted into (A3.2), produces

$$\frac{dS_E}{dP_E} = \left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left(\frac{dS_C}{dP_C} - \frac{dD_D}{dP_C} - \frac{dD_X}{dP_C}\right) \tag{A3.4}$$

Manipulating equation (A3.4), we arrive at

$$\frac{dS_E}{dP_E}\frac{P_E}{S_E}\frac{S_E}{P_E} = \left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left(\frac{dS_C}{dP_C}\frac{P_C}{S_C}\frac{S_C}{P_C} - \frac{dD_D}{dP_C}\frac{P_C}{D_D}\frac{D_D}{P_C} - \frac{dD_X}{dP_C}\frac{P_C}{D_X}\frac{D_X}{P_C}\right) \tag{A3.5}$$

and after the conversion into elasticities and rearrangement we obtain

$$\eta_{SE} = \left(\frac{\lambda\beta}{1-r\gamma}\right)^2\left(\eta_{SC}\frac{S_C}{P_C} - \eta_{DD}\frac{D_D}{P_C} - \eta_{DX}\frac{D_X}{P_C}\right)\frac{P_E}{S_E} \tag{A3.6}$$

where η_{SE}, η_{SC}, η_{DD} and η_{DX} denote the elasticities of ethanol supply, corn supply, domestic non-ethanol corn demand and export corn demand, respectively.

Finally, reapplying the definitions of P_C and S_E, the ethanol supply elasticity simplifies to

$$\eta_{SE} = \left(\eta_{SC} \frac{S_C}{S_C^E} - \eta_{DD} \frac{D_D}{S_C^E} - \eta_{DX} \frac{D_X}{S_C^E} \right) \frac{P_E}{P_E - c_0} \tag{A3.7}$$

where S_C^E denotes the quantity of corn (exclusive of the recycling effect) used as an input to ethanol production. Note that the bracketed term in equation (A3.7) is an elasticity of the ethanol supply expressed in bushel terms. Because $P_E / (P_E - c_0) > 1$, such an elasticity is always lower than its proper counterpart in the ethanol space.

Appendix 4. Data Sources

Parameter/Variable	**Source/explanation**
U.S. fuel tax	American Petroleum Institute
U.S. blender's tax credit	Federal plus state tax credit
Ethanol production subsidy	Koplow (2009)
Corn production subsidy	Environmental working group
U.S. gasoline consumption	Energy Information Administration
Foreign gasoline consumption	Energy Information Administration
U.S. gasoline supply	Energy Information Administration
Foreign gasoline supply	Energy Information Administration
Ethanol consumption	Energy Information Administration
Gasoline price	Unleaded gasoline average rack prices F.O.B. Omaha, Nebraska
Price of fuel	calculated
U.S. production of yellow corn	USDA WASDE reports (various years)
U.S. domestic consumption of non-ethanol yellow corn	USDA WASDE reports (various years)
U.S. corn exports	USDA WASDE reports (various years)
Quantity of corn for ethanol production	USDA WASDE reports (various years)
Ethanol price	Ethanol average rack prices F.O.B. Omaha, Nebraska
Lambda (λ)	de Gorter and Just (2008)
Beta (β)	Eidman (2007)
Gamma (γ)	Eidman (2007)
Relative price of ethanol cy-product and corn	Lawrenceburg, Indiana as reported by the USDA AMS
Ethanol processing cost	calculated
Corn market price	ERS of USDA, (average prices received by farmers, United States)
U.S. fuel demand elasticity	(-0.20) de Gorter and Just (2009b)
Foreign fuel demand elasticity	(-0.32) calculated to obtain the elasticity of the excess supply of gasoline equal to 3 (Cui et al. 2011)
U.S. gasoline supply elasticity	(0.20) de Gorter and Just (2009b)
Foreign gasoline supply elasticity	(0.15) assumed
Elasticity of yellow corn supply	(0.23) de Gorter and Just (2009b)
Elasticity of U.S. demand for non-ethanol yellow corn	(-0.20) de Gorter and Just (2009b)
Elasticity of yellow demand for U.S. corn exports	(-1.5) Cui et al. (2011)

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CHAPTER 2

An Economic Model of Brazil's Ethanol-Sugar Markets and Impacts of Fuel Policies[36]

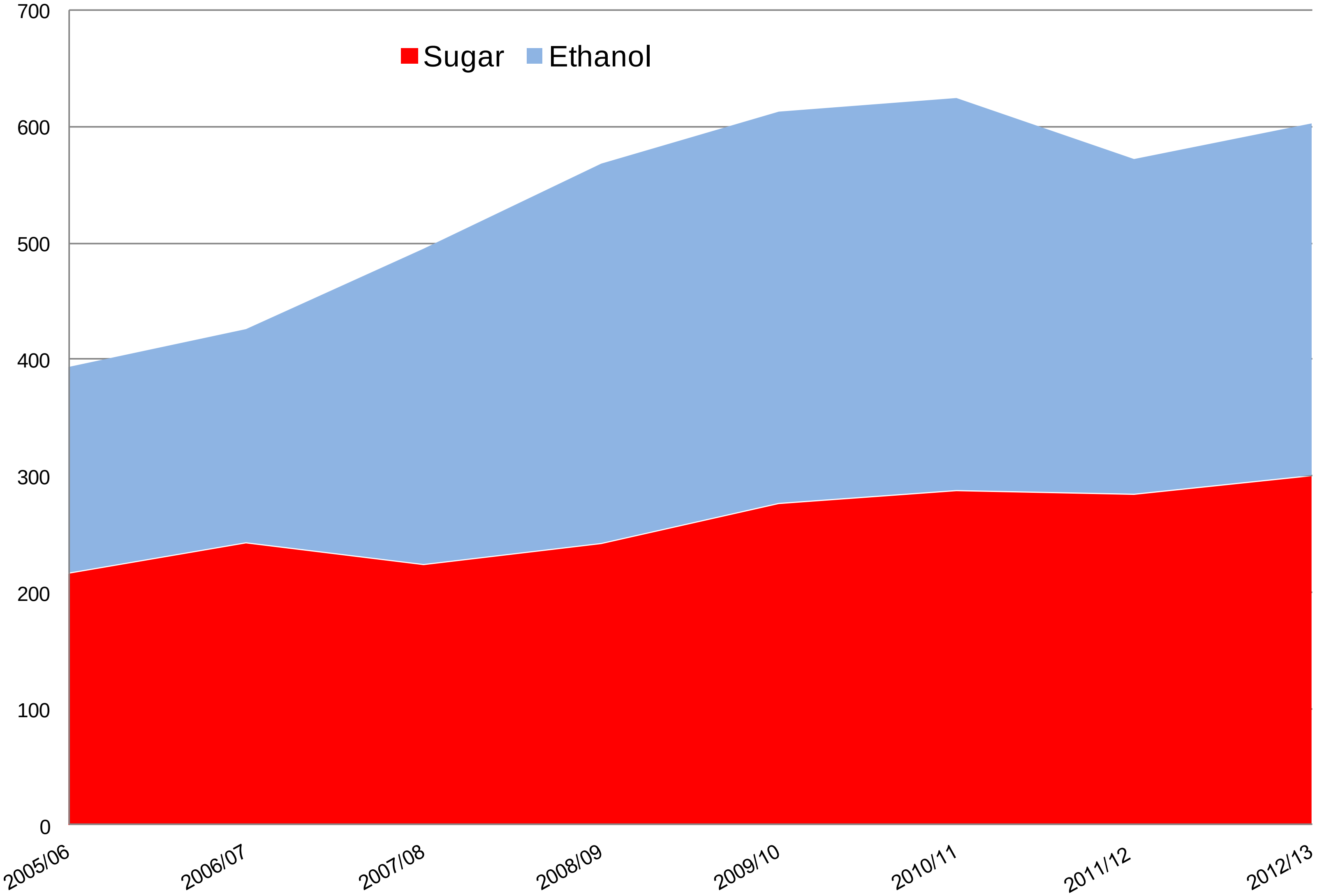
1. Introduction

Brazil has developed a unique system of producing competing tradable products – sugar and ethanol – from non-traded sugarcane. Modern "flex-plants" can produce either sugar or ethanol from sugarcane, and within a production year, can switch between the two products up to about 65 percent of a product.[37] Furthermore, flex-plants can extract up to 18.6 liters of ethanol per tonne of sugarcane processed into sugar from molasses, a by-product of sugar production (Gopal and Kammen 2009).[38] The total output of sugarcane is shown in Figure 1; ethanol's share of sugarcane has ranged between 45 and 57 percent in the past 7 years.[39]

Brazil is the biggest sugar producer in the world (25 percent of the world total), the biggest sugar exporter (60 percent of the world total) and until overtaken by the United States recently, the world's biggest ethanol producer and exporter. Hence, the world prices of sugar and ethanol would be expected to be directly linked and not diverge significantly, given the economics of sugarcane processing in Brazil. Figure 2 gives evidence that this may be the case. Brazil is regarded as the lowest cost producer of ethanol in the world but since mid-2009 to mid-2012, Brazil's market price of ethanol was higher than the U.S. price and Brazil became a major importer of U.S. ethanol. The reasons for high ethanol prices in Brazil in this time period are manifold, including strong domestic demand for transportation fuels, increasing demand for

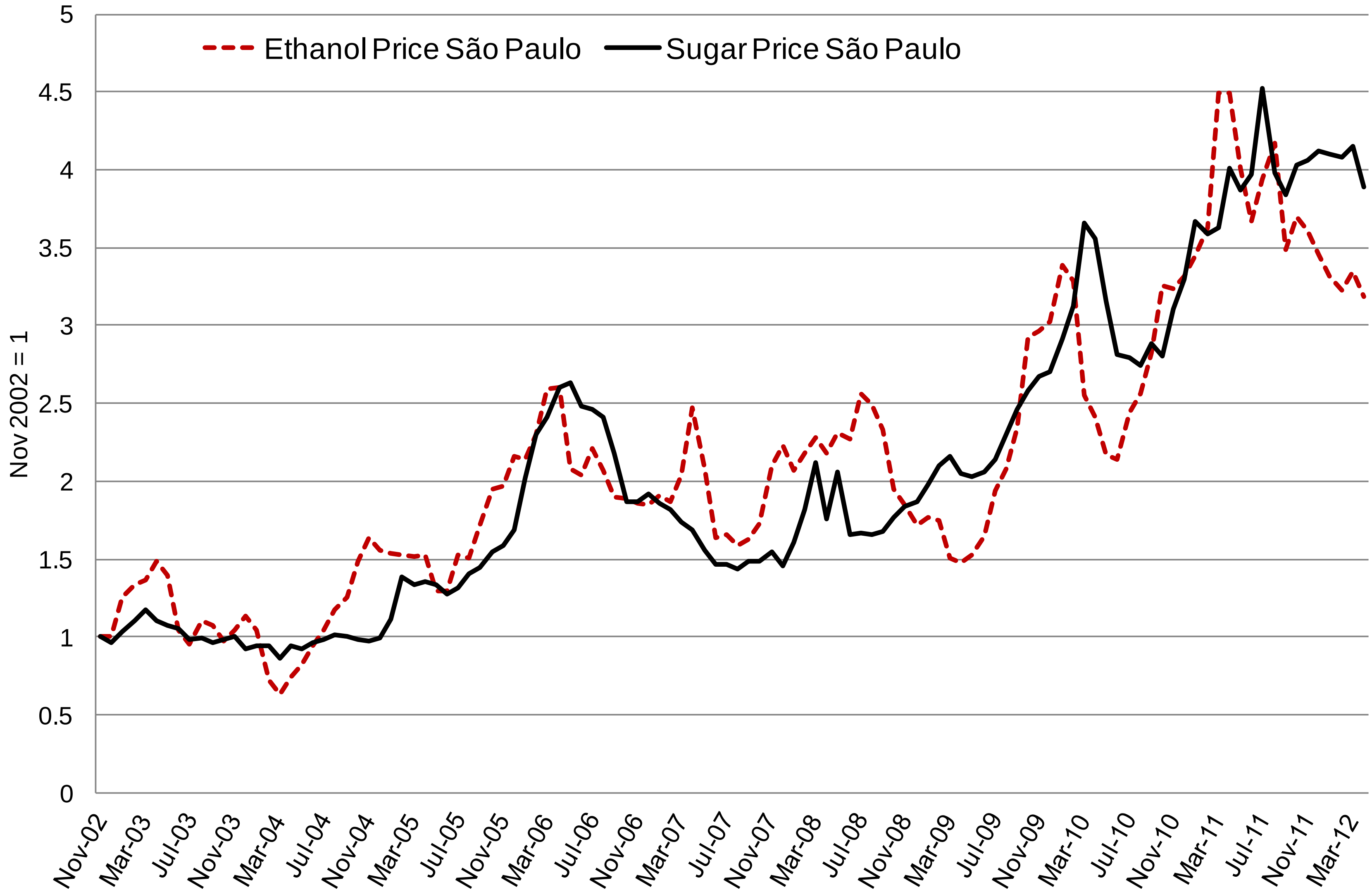
[36] This chapter is forthcoming as a World Bank working paper and has been coauthored with Harry de Gorter, Erika M. Kliauga, and Govinda R. Timilsina.
[37] About 300 plants today are flex-plants, accounting for a substantial share of total sugarcane processed. The other plants are either dedicated to ethanol only (125 plants in 2010, UNICA) or sugar only (12 plants, UNICA).
[38] Molasses is therefore, in theory, a very important source of ethanol because if 55 percent of total sugarcane production were devoted to sugar production, and every plant maximized ethanol production from molasses, then 25 percent of total ethanol production in Brazil could come from molasses alone. But plants dedicated to just sugar production find it uneconomical to extract ethanol from molasses.
[39] Another unique aspect of processing sugarcane into ethanol and sugar is that the bagasse (leftover biomass) can be burned for electricity production to be used by the plant itself with excess electricity sold on the grid.

Figure 1. Brazil Sugarcane Processed (million tonnes)



Source: CONAB (Brazilian Food Supply Agency)

Figure 2. Brazilian Ethanol versus Sugar Prices (Index)



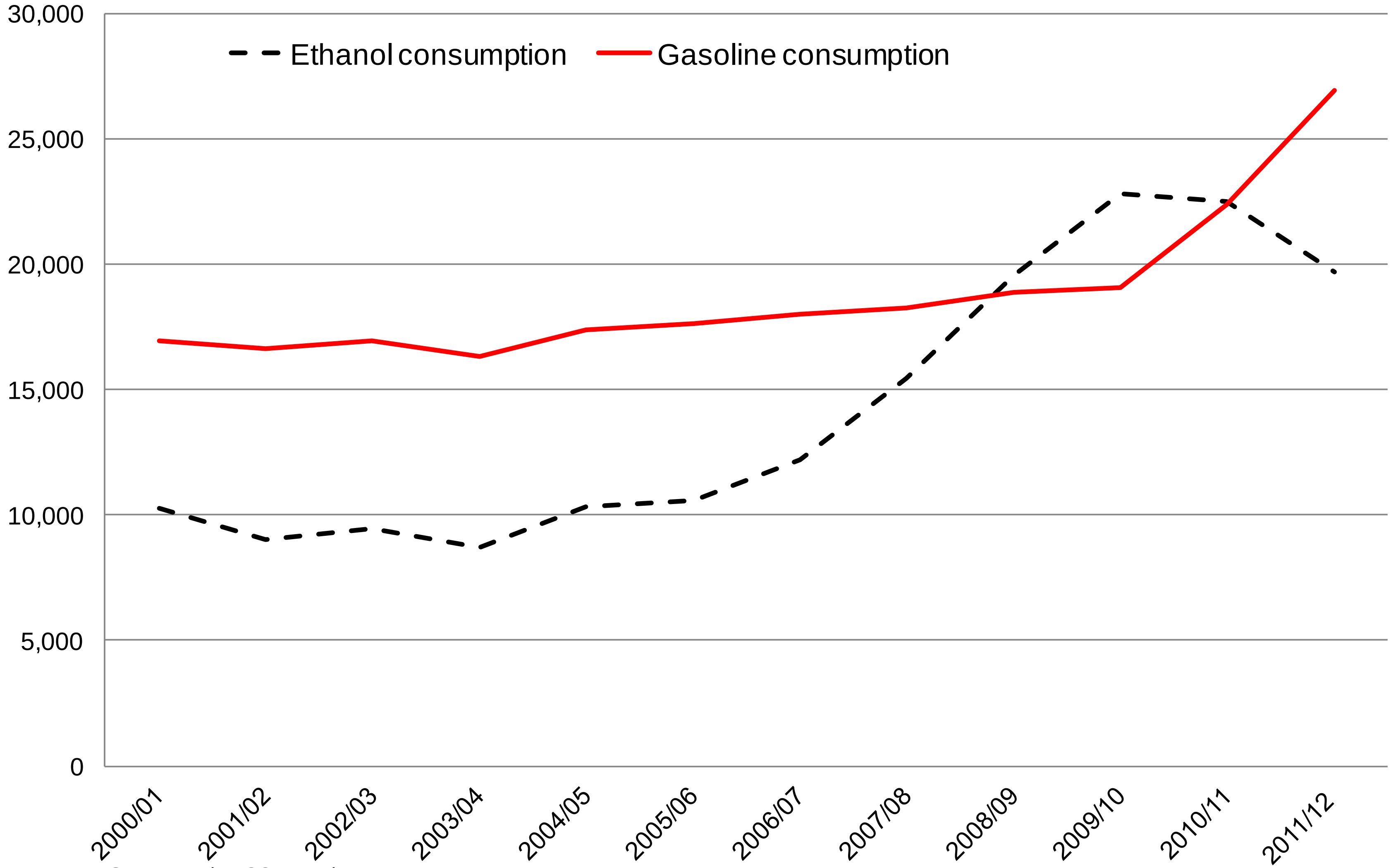
sugar with world record sugar prices, and bad weather affecting the sugarcane harvest at home and abroad. The impact of the Brazilian government's ethanol policies is also blamed for inadequate domestic supplies of ethanol due to lack of investment since the 2008 financial crisis (Jank 2012), an issue we will pay close attention to in this paper.

Brazil has two different demand curves for ethanol in transportation fuel: an *anhydrous* ethanol and gasoline fuel mixture (which we define as "fuel" in this paper) that all cars can consume, and E-100 (100 percent *hydrous* ethanol) which only flex cars[40] can consume (23 percent of total cars in Brazil are currently flex but this fraction is growing fast and over 80 percent of new car sales in the past two years were flex).[41] Strong domestic demand for ethanol in Brazil is due to growing incomes. Recently, about 50 percent of total gasoline plus ethanol consumed in Brazil has been ethanol, compared to 10 percent in the United States. Gasoline consumption in Brazil increased by 2 bil. liters from 2000/01 to 2009/10 but ethanol consumption increased by a whopping 24 bil. liters. But since 2009, total ethanol consumption (hydrous and anhydrous) has declined by almost 20 percent (Figure 3) as rising ethanol prices, along with lower gasoline taxes and gasoline prices being pegged below world prices (Figure 4), have all contributed to a higher share of gasoline being consumed.

The share of anhydrous ethanol consumption of total ethanol consumed has increased from 33 percent in 2009/10 to 45 percent in 2011/12. The reason for this development is not just higher ethanol prices but also a narrowing of the "parity gap" between E100 and fuel prices. The price of E100 is usually discounted to the price of fuel in terms of the cost per kilometer traveled (cars get about 30 percent less kilometers per liter of E100 relative to fuel). The price of E100 at parity is denoted by the dotted line in Figure 5. Historically, E100 prices were at a substantial

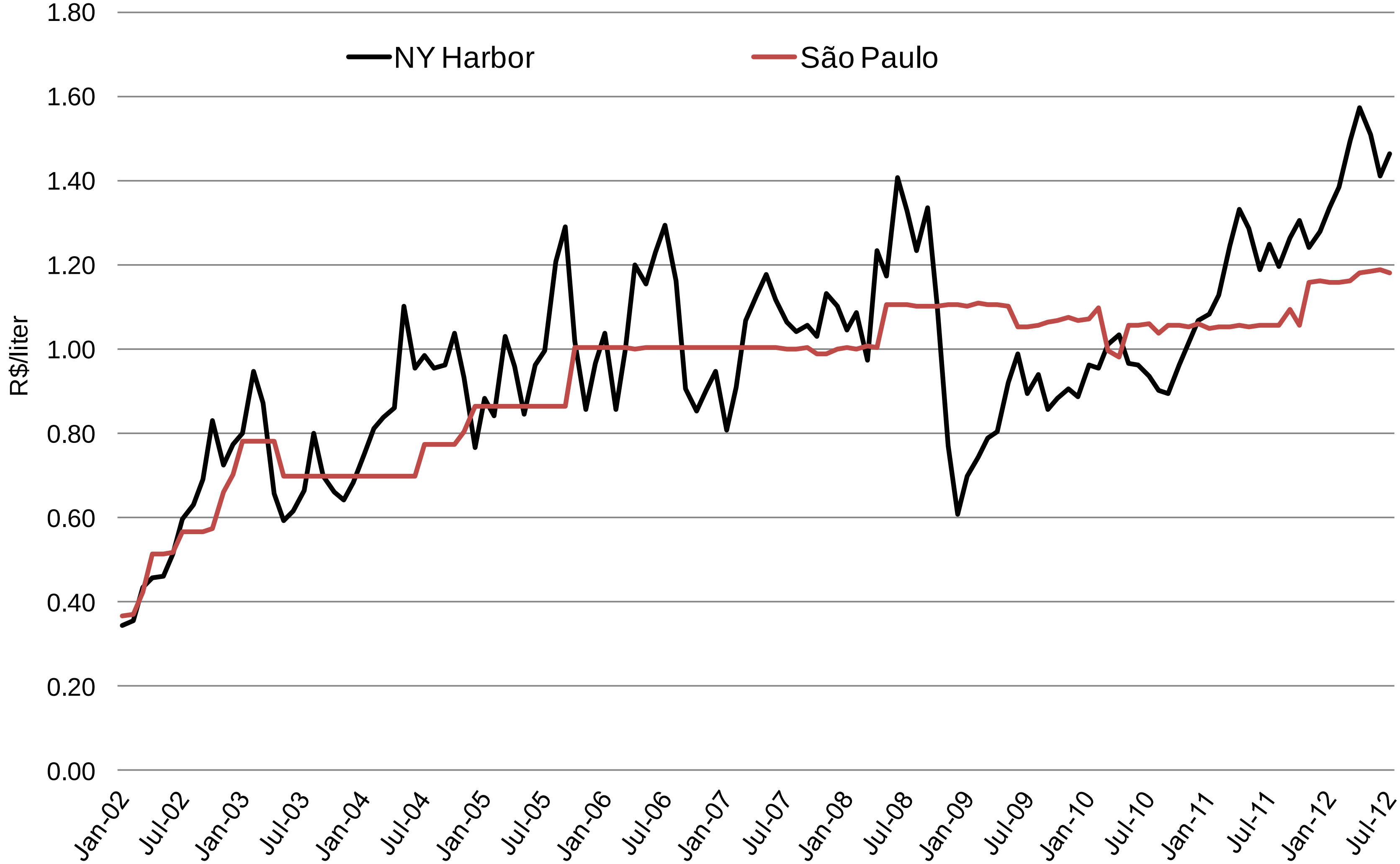
[40] A flex car can run on fuel with the share of ethanol between zero and 100 percent.
[41] The Brazilian government also gives tax breaks for the purchase of flex cars.

Figure 3. Gasoline versus Ethanol Consumption in Brazil (million litres)



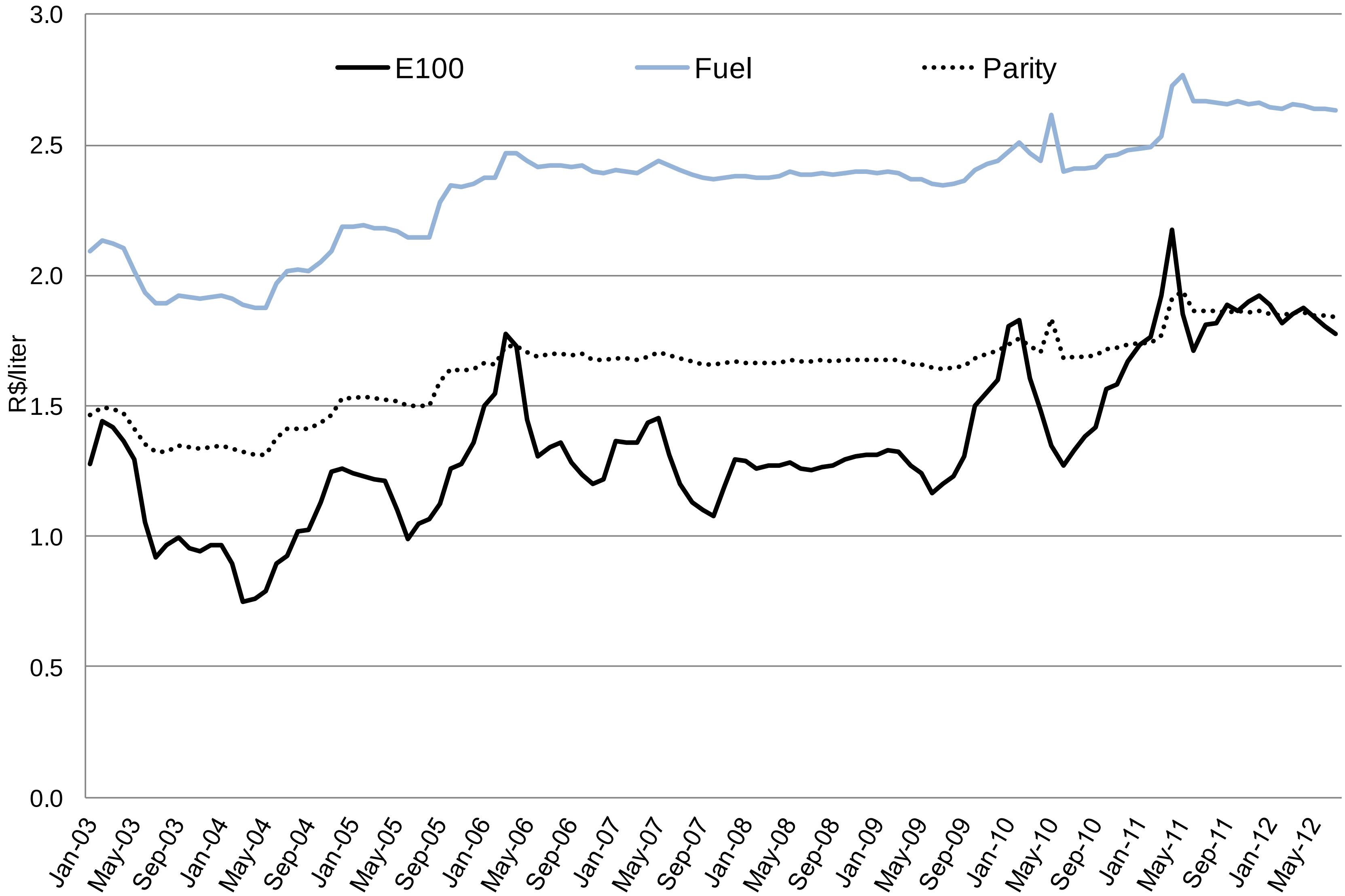
Source: Using CONAB data

Figure 4. U.S. and Brazil Gasoline Prices Compared



Source: Brazil ANP, U.S. EIA

Figure 5. Fuel Prices in São Paulo



Source: ANP 2012

discount to fuel (adjusted for the differential kilometers per liter), often reaching levels 25 percent lower than the fuel price. This encouraged the adoption of flex cars and infrastructure like E100 dispensing stations. As the share of flex cars has increased, and with higher ethanol prices, this discount has disappeared in the past 2-3 years.

The market price of anhydrous ethanol exceeds that of hydrous ethanol because more sugarcane is required to produce a gallon of anhydrous ethanol and there are additional non-sugarcane related production costs associated with anhydrous production. Because sugarcane is used to produce sugar, hydrous ethanol and anhydrous ethanol, then it must be that for a flexible plant – modeled in this paper – the marginal benefits of these three production processes are equal (adjusted for ethanol from molasses, a by-product from sugar production).

Brazilian ethanol policies are also important factors affecting the sugar/ethanol markets and can be classified into four categories. First, Brazil has a mandate for anhydrous ethanol mixed with gasoline, requiring 18 to 25 percent of the total fuel mixture to be anhydrous ethanol, depending on supply-demand conditions (currently 20 percent, down from 25 percent in October 2011).[42] Second, E100 sales enjoy a tax exemption that is greater than what is needed to compensate for the fewer kilometers obtained relative to a liter of the gasoline-anhydrous fuel mixture. The tax on anhydrous ethanol is even lower, although as we show later, consumers only see the E25 price. Third, the Brazilian government has often in the past, and again recently, held the price of gasoline below world prices. Fourth, the federal government has recently eliminated the fuel tax. We show that in theory each of these policies has an ambiguous impact on ethanol market prices, but empirically we determine that a higher gasoline price, mandate and tax exemption for hydrous ethanol results in higher ethanol prices, but a lower gasoline tax and a higher tax exemption on anhydrous ethanol results in lower ethanol prices.

[42] There is currently much political discussion in Brazil to increase the mandate back to 25 percent.

The primary objectives of this paper are to (a) develop a general economic model of the Brazilian fuel-ethanol-sugar complex that reflects sugarcane processing flex-plants that produce both sugar and ethanol, with the world prices of each product determined endogenously; and (b) determine the economic effects of Brazil's ethanol policies. To that end, we incorporate unique features of Brazil's markets and policies into the economic model; specifically, we model the two fuel demands and the anhydrous ethanol mandate, the changing parity gap between E100 and fuel prices, ethanol produced from molasses, the by-product of sugar production, and bagasse for electricity production. We use our model to explain the dramatic change in market conditions from 2010/11 to 2011/12 when ethanol and sugar prices soared, fuel consumption increased, sugarcane production fell and the share of sugarcane processed into ethanol declined.

The rest of this paper is organized as follows. After a brief description of how our approach relates to the literature, we develop an analytical model in Section 3. In Section 4, we incorporate the shift in the demand curves for fuel and E100. Section 5 presents the comparative static results. Data and calibration used in our empirical model are described in Section 6. In Section 7, we empirically illustrate our results; the last section provides some concluding remarks.

2. Relation to the Literature

There is a fledgling literature on the market effects of Brazilian ethanol policies. One of the first studies is Schmitz et al. (2003). Like in Elobeid and Togkoz (2008), who analyze the effects of U.S. ethanol policies on Brazilian markets, their economic representation of Brazil's sugarcane-ethanol industry is simplistic and there is a lack of detail in depicting the effects of various policies. Kliauga et al. (2010) hypothesize that through 2008, the U.S. tax credit determined the world ethanol price and the Brazilian price was often linked to it. Using time series techniques, Rajcaniova et al. (2011) test the theory of Kliauga et al. but find only partial support for it. They find that Brazil and the United States co-determined the ethanol market price in the period 2002–2010.

A recent strand of the literature has focused on the analysis of the ethanol-sugar-oil nexus in Brazil (and also on ethanol-corn-oil long run relationships elsewhere). For example, Balcombe and Rapsomanikis (2008) study the long-run price relationships among the three commodities using monthly data for the period 2000 – 2006. They use a bivariate error correction model and allow for non-linear adjustment toward the equilibrium. Oil prices were found to determine the long-run equilibria of both sugar and ethanol prices and sugar prices were found to cause ethanol prices but not the other way around. A recent paper by Serra et al. (2011) also uses time-series econometric techniques to investigate price volatility transmission in the Brazilian ethanol industry in the period 2000-2008. Akin to Balcombe and Rapsomanikis (2008), ethanol, sugar, and oil prices are analyzed. Serra et al. (2008) find a strong link, both for levels and volatility, between food and energy markets. Their impulse-response analysis shows that an increase in crude oil prices leads the system towards a new equilibrium with higher ethanol prices. Increases in sugar prices are also found to increase ethanol price levels and volatility (see also Serra 2011).

What Balcombe and Rapsomanikis (2008) and Serra et al. (2011) fail to recognize, however, is that it is gasoline, not oil, which links ethanol to sugarcane (and sugar). Moreover, the Brazilian government fixes gasoline prices through Petrobras, a publically traded company in which it is the biggest shareholder (de Miranda 2010; Zilberman 2012). Under such regulation, the domestic gasoline prices are delinked from the world oil prices which they would follow under a free market (see Figure 4).

Papers in the earlier strand of econometric literature share two common features. First, many studies analyze periods ending in 2007 or 2008; second, they investigate the long run relationships among the prices. Unlike the econometric studies, our paper provides a structural model that takes a detailed account of the unique features of the Brazilian sugar-ethanol market. The advantage of our methodology is that it is also able to explain recent significant (short-term) shocks in the market. Our paper also extends the existing biofuels literature (e.g., de Gorter and Just 2009; Lapan and Moschini 2012) by incorporating two demand curves for ethanol and modeling the endogenous decision of flex cars owners to shift between consumption of fuel and hydrous ethanol.

While the time-series models discussed above concentrate on the linkage among commodity prices, structural models for the Brazilian and U.S. ethanol markets focus more on the relative competitiveness of sugarcane and corn ethanol. Thus, for example, Crago et al. (2010) find that although the cost of sugarcane ethanol production in Brazil is lower than that of corn ethanol in the United States, once transportation costs for the sugarcane ethanol and the value of corn-related Dried Distiller Grain Solubles (DDGS) are included, the relative competitiveness changes. They also find that the relative cost of ethanol in the United States and Brazil is very sensitive to the prevailing exchange rate and prices of feedstocks. This is of particular importance as the Brazilian Real has appreciated about 30 percent in value relative to the U.S. dollar in the last half decade (de Gorter et al. 2012).

The existence of a unique system of flexible plants in Brazil which are able to adjust their production program in favor of either sugar or ethanol, depending on their relative prices, substantially improves the profitability of the Brazilian sugarcane processing sector. Other significantly contributing factors are government policies and market developments. We now analyze these aspects of the Brazilian market.

3. The Model

Consider a competitive industry that processes sugarcane into three products: sugar, anhydrous ethanol and hydrous ethanol. Sugar and ethanol are competing products because the industry can adjust, although only to a certain extent, the allocation of sugarcane, depending on the relative market price of sugar and ethanol.[43] A by-product of sugarcane processing, regardless of the use of the sugarcane, is bagasse. Bagasse is a fibrous matter that is burned in special boilers whereby electricity and steam used in sugarcane processing are cogenerated.[44] Sugar production also yields a by-product – molasses, which is further used to produce anhydrous and hydrous ethanol.

For internal consistency of our model, we express all quantities related to the fuel market (i.e., ethanol and gasoline) in gasoline energy-equivalent liters (GEEL).[45] A typical Brazilian flexible sugarcane processing plant extracts $\delta = \delta_A + \delta_H = 6.20$ GEELs[46] of ethanol from one metric tonne of sugarcane processed into sugar; the parameters δ_A and δ_H denote GEELs of anhydrous and hydrous ethanol from one metric tonne of sugarcane, respectively.[47]

The burning of bagasse makes Brazilian flex plants self-sufficient in the electricity they need to process sugarcane into individual products. The excess supply of electricity is sold to the grid at the market price. Denote ρ_{SC} as the number of kilowatt hours (kWhs) of electricity

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[43] In a modern Brazilian "flex" sugarcane processing plant, the share of sugarcane going to sugar can vary between 40 and 60 percent.

[44] The burning of the sugarcane straw for electricity cogeneration is currently not economical because of substantial transportation costs of hauling the straw to the processing plant.

[45] One gasoline energy-equivalent liter denotes a volume of fuel that contains the same energy as one liter of gasoline. In converting fuel quantities to GEELs, we assume that one physical liter of anhydrous and hydrous ethanol yield only 67 percent of vehicle kilometers traveled relative to gasoline. In Brazil, one liter of hydrous ethanol yields 70 percent of kilometers traveled on one liter of the 25 percent fuel blend (25 percent of anhydrous ethanol and 75 percent of gasoline).

[46] This corresponds to 9.25 liters.

[47] Molasses from one tonne of sugarcane could potentially yield as much as 18.6 liters of ethanol (Gopal and Kammen 2009). This yield is expected for new modern production plants.

produced from bagasse extracted from one metric tonne of sugarcane, ρ_i as the number of kWhs of electricity required to produce one unit of product i, ϕ_i as the yield (in tonnes or GEELs) of product i per tonne of sugarcane, and P_M and P_I as the market and internal (to the processing plant) price of electricity, where $i = \{S,\ H,\ A\}$ and S, H, and A denote sugar, hydrous ethanol, and anhydrous ethanol, respectively. The profit from electricity generation per tonne of sugarcane processed for product i is thus given by

$$\Psi_i = P_M\left(\rho_{SC} - \phi_i \rho_i\right) - P_I \phi_i \rho_i \tag{1}$$

The first term on the right-hand side of equation (1) denotes the revenue from selling the excess supply of electricity at the market price. The second term represents the internal cost of producing electricity from bagasse. We assume that the electricity prices are exogenous to the processing plant, which makes Ψ_i a parameter in the consequent analyses. Notice also that although the observed market price of electricity is higher than the internal price (i.e., $P_M > P_I$), the profit from electricity generation might be negative, depending on the relative size of the excess supply and internal consumption of electricity.

We assume that production of sugar and ethanol exhibits constant returns to scale. A competitive industry will allocate the sugarcane into sugar, hydrous and anhydrous ethanol so that each production process earns zero marginal profits in equilibrium[48]

$$P_{SC} = \phi_S P_S + \delta_H P_H + \delta_A P_A + \Psi_S - \phi_S \xi_S \tag{2}$$

$$P_{SC} = \phi_H P_H + \Psi_H - \phi_H \xi_H \tag{3}$$

$$P_{SC} = \phi_A P_A + \Psi_A - \phi_A \xi_A \tag{4}$$

[48] Our model represents long run equilibria in the relevant markets.

Equation (2) comes from a zero profit condition for sugar production and takes into account the additional quantity of ethanol that can be produced from molasses. In equation (2), P_{SC} and P_S denote market prices of sugarcane and sugar (measured in \$/tonne), respectively, and P_H and P_A denote market prices of hydrous and anhydrous ethanol (measured in \$/GEEL), respectively. The parameter ξ_S denotes (constant) processing cost (other than the cost of feedstock and electricity) per tonne of sugar.

Equation (3) relates prices of sugarcane and hydrous ethanol while equation (4) links the prices of sugarcane and anhydrous ethanol. The processing costs per GEEL of hydrous and anhydrous ethanol are denoted by ξ_H and ξ_A, respectively.

On the supply side, the market prices of hydrous and anhydrous ethanol are linked through the cost of feedstock (sugarcane) and processing cost of hydrous and anhydrous ethanol as follows

$$P_A - P_H = \xi_A - \xi_H - \left(\frac{\Psi_A}{\phi_A} - \frac{\Psi_H}{\phi_H} \right) + \left(\frac{1}{\phi_A} - \frac{1}{\phi_H} \right) P_{SC} = \beta_0 + \beta_1 P_{SC} \qquad (5)$$

Equation (5), obtained by the summation and rearrangement of equations (3) and (4), shows that the gap between anhydrous and hydrous ethanol market prices widens as the price of sugarcane increases. This occurs because the production parameters satisfy $\phi_A < \phi_H$, implying that production of one gallon of anhydrous ethanol is less efficient. This puts anhydrous ethanol at a relative disadvantage because consumers have to pay a higher (fuel) price to compensate producers of anhydrous ethanol for the higher production cost and lower efficiency.

Competition among fuel blenders results in zero profits (up to a constant marketing margin m_F) which implies a link between the fuel price paid by consumers, P_F, the price of anhydrous ethanol and the exogenous gasoline market price, P_G

$$P_F = \alpha\left(P_A + t_A\right) + \left(1 - \alpha\right)\left(P_G + t_G\right) + m_F \tag{6}$$

where α denotes an energy-equivalent blend mandate, and t_A and t_G denote taxes on anhydrous ethanol and gasoline (measured in \$/GEEL), respectively.[49] We assume that the gasoline price is exogenous to fuel blenders because the Brazilian government regulates gasoline prices through Petrobras and ethanol production is assumed not to affect world oil prices.

Similarly, the consumer price of hydrous ethanol (E100) is determined by

$$P_{E100} = P_H + t_H + m_{E100} \tag{7}$$

where, t_H denotes the E100 fuel tax and m_{E100} denotes a constant marketing margin.

The market equilibrium requires that the supply of sugarcane, S_{SC}, equals the sum of individual uses of sugarcane: sugar and anhydrous and hydrous ethanol

$$S_{SC}\left(P_{SC}\right) = C_{SC}^S + \frac{D_H + I_H}{\phi_H} - \frac{\delta_H C_{SC}^S}{\phi_H} + \frac{\alpha D_F + I_A}{\phi_A} - \frac{\delta_A C_{SC}^S}{\phi_A} \tag{8}$$

The first term on the right-hand site of equation (8), C_{SC}^S, is the quantity of sugarcane allocated to production of sugar. The second term represents the total quantity of sugarcane corresponding to production of hydrous ethanol. Hydrous ethanol used in the domestic transportation sector is denoted by D_H and the quantity of ethanol used in the domestic non-transportation sector is denoted by I_H; the latter is assumed to be exogenous. The third (negative) term accounts for the hydrous ethanol produced from molasses. This quantity needs to be subtracted in order to avoid double counting: the total allocation of sugarcane for hydrous ethanol has already been accounted for in the second term.

[49] The Brazilian blend mandate requires that α [x100] percent of total fuel volume be anhydrous ethanol, i.e., $\alpha = A/\left(A+G\right)$, where A denotes the quantity of ethanol and G denotes the quantity of gasoline. By converting A into GEELs, we express the mandate in energy-equivalent terms.

The fourth term in equation (8) denotes allocation of sugarcane used for production of anhydrous ethanol. Akin to hydrous ethanol, anhydrous ethanol is used in the domestic transportation sector, in quantity αD_F, but it can also be exported or used in other industries. The quantity for the latter two uses is denoted as I_A and is assumed to be determined exogenously. The last (negative) term again adjusts for the anhydrous ethanol extracted from molasses.

We close the model by equilibrating the sum of domestic and foreign demand for sugar, D_S^D and D_S^W, respectively, with sugar production

$$D_S^D\left(P_S\right)+D_S^W\left(P_S\right)=\phi_S C_{SC}^S \tag{9}$$

An intrinsic feature of the model outlined above is its relative "stability", since changes in policy parameters have small market effects: even if we change all the policy parameters (the blend mandate, taxes and gasoline price) and technology parameters (yields of sugar, hydrous and anhydrous ethanol from one tonne of sugarcane) that changed from the 2010/11 to the 2011/12 levels, the impact on the market is modest and in no way reproduces the market changes from 2010/11 to 2011/12 (we will show this empirically later). This suggests that there were major exogenous shocks to the Brazilian sugar-ethanol market complex during this time period, other than the biofuel policy changes. These shocks came in the form of bad weather (shifting the sugarcane supply curve in by about 18.3 percent, according to our estimates), income growth that increased the number of cars and kilometers driven (thereby shifting out demand for fuel), and a major shift in export demand for sugar, as evidenced by record world sugar prices. All these shocks would be manifest in shifting the demand/supply curves for fuel, ethanol, sugar and/or sugarcane. To explain the significant increase in the market prices of the modeled commodities, it is therefore important to quantify the shifts in market demand/supply curves.

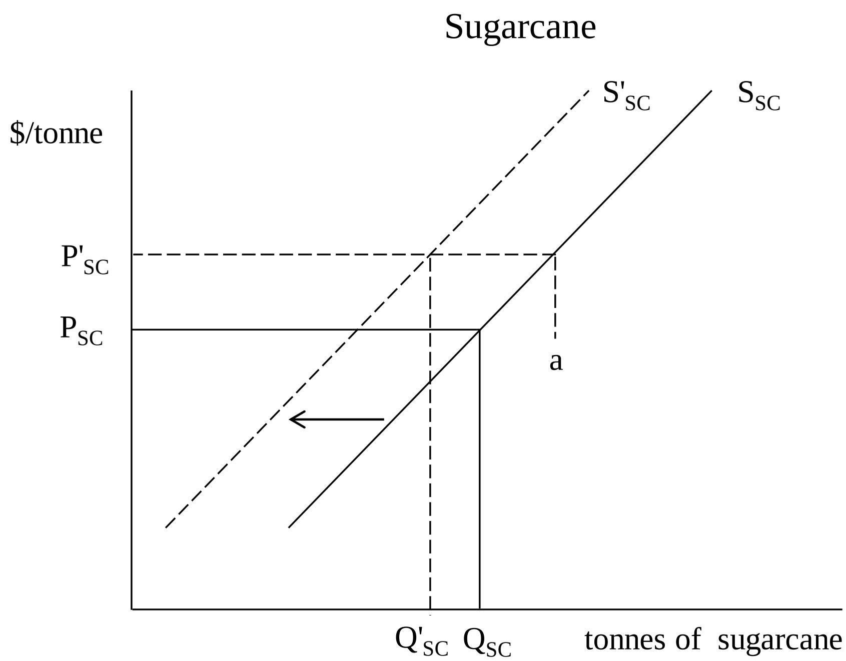
The sugarcane supply curve in 2010/11 is depicted in the upper panel of Figure 6a, denoted by S_{SC} with a corresponding equilibrium price-quantity pair P_{SC} and Q_{SC}, respectively. The price of sugarcane in the 2011/12 marketing year increased to P'_{SC}, while the quantity supplied reduced to Q'_{SC}. As shown in Figure 6a, this implies an inward shift in the sugarcane supply curve, represented by S'_{SC}. The size of the parallel shift is given by distance $Q'_{SC}a$ and is calculated as $S_{SC}\left(P'_{SC}\right)-Q'_{SC}$, where the first term represents what the supply of sugarcane would have been if the price had increased to P'_{SC} along the original supply curve.[50]

The lower panel of Figure 6a depicts a shift in the aggregate demand for sugar. Both domestic and export demand experienced an outward shift, and we model them separately in the numerical part of our paper. Unlike in the upper panel, a decrease in consumption of sugar combined with an increase in its market price is not sufficient to conclude that the demand shifts in. To see this, consider the intersection of the demand curve D_S with the vertical dashed line corresponding to C'_S. If the price P'_S were below this point (but above P_S), the new demand curve would be to the left of the original one. However, the observed data show that the demand for sugar (both domestic and exports) shifted out. The size of the shift is given by $C'_S - D_S\left(P'_S\right)$. Shifts in demands for fuel and hydrous ethanol are determined in a similar way (Figure 6b).

To see how the assumed elasticities of the demand and supply curves depicted in Figure 6a and 6b affect the size of the shift, we estimate the shifts under three scenarios – low, medium, and high – as shown in Table 1.

[50] This result holds also for non-linear curves, used in our numerical simulations because the shift is horizontally parallel.

Figure 6a. Estimated Shifts in Sugarcane Supply and Sugar Demand



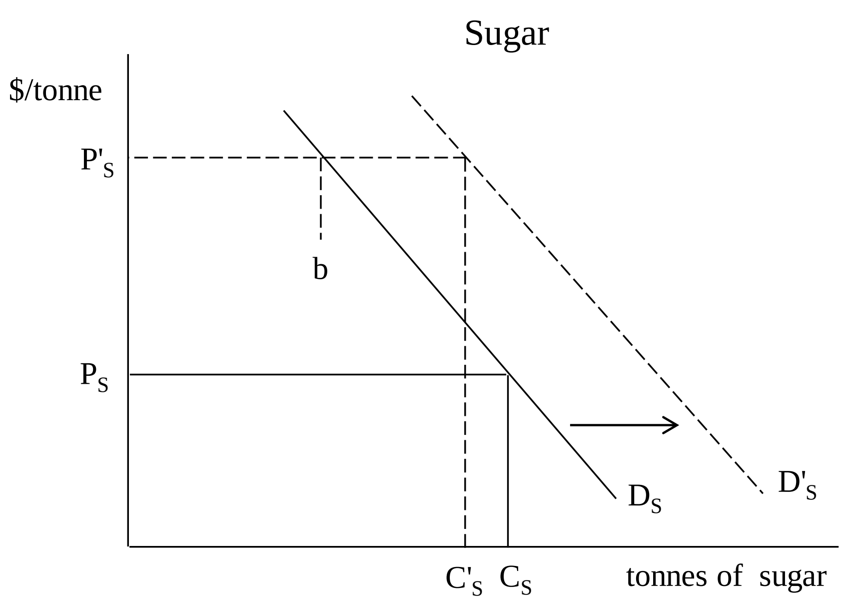
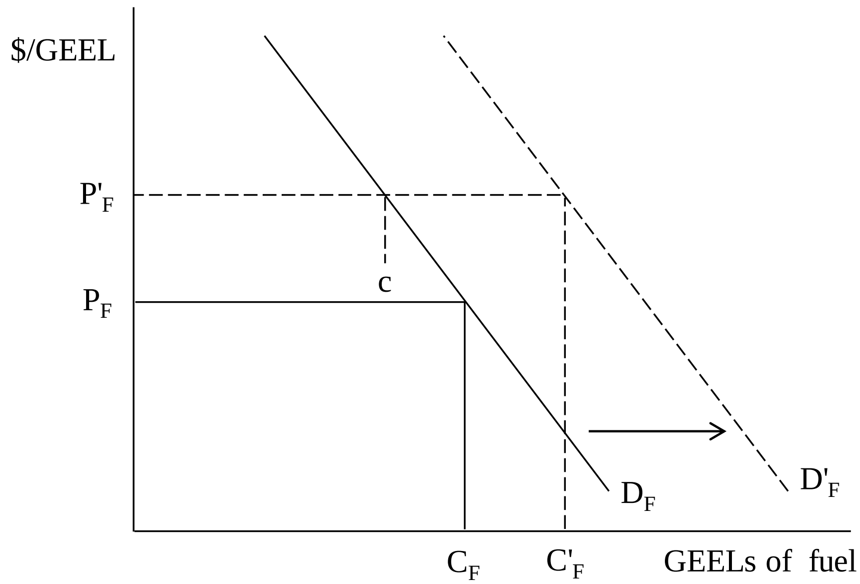


Figure 6b. Estimated Shifts in Fuel and Hydrous Ethanol Demand

Fuel



Hydrous ethanol

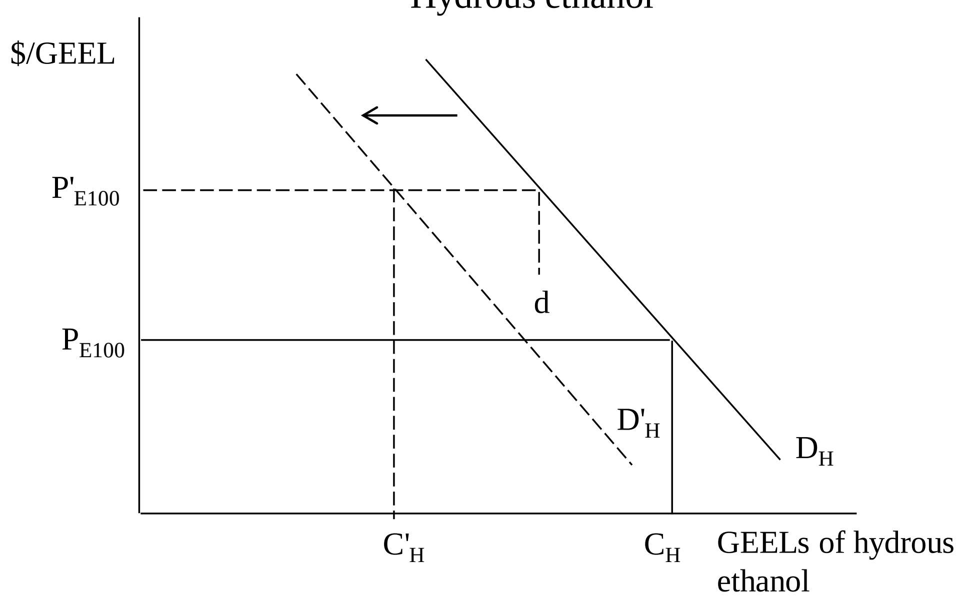


Table 1. Elasticities Used in Simulations to Detemine Exogenous Shifts in Supply and Demand Curves	Low	Medium	High
Sugar supply	0.00	0.50	0.70
Fuel demand	-0.09	-0.23	-0.40
Hydrous ethanol demand	-0.30	-0.68	-0.80
Domestic demand for sugar	-0.50	-0.75	-1.00
Export demand for sugar	-1.00	-2.00	-4.00

Table 2 presents estimates of the shifts in individual markets in absolute and relative terms (we measure the size of the shift as a percentage of the 2010/11 consumption/production level). We focus on the medium elasticity scenario, noting that more elastic market curves are associated with greater shifts (with the exception of the hydrous ethanol demand, where the more elastic demand yields a smaller shift). The first column under each scenario presents the level of a shift. A negative value indicates a shift to the left. In the second column, we report the size of the shift as a percentage of the 2010/11 (baseline) production/consumption. Although all shifts are significant in magnitude, the 22.8 percent increase in fuel demand and the 33.8 percent increase in foreign demand for Brazilian sugar are noticeably high in the medium scenario.

Table 2. Estimated Shifts in Brazilian Sugar and Fuel Markets between 2010/11 and 2011/12

	Low elasticity		Medium elasticity		High elasticity	
Shift in…	Size*	% of 2010/11 quantity	Size	% of 2010/11 quantity	Size	% of 2010/11 quantity
Sugarcane supply (bil. tonnes)	-0.052	8.4	-0.114	18.3	-0.141	22.6
Fuel demand (bil. liters)	6.662	21.8	6.965	22.8	7.315	24.0
Hydrous ethanol demand (bil. liters)	-4.209	27.5	-3.144	20.6	-2.838	18.6
Domestic demand for sugar (bil. tonnes)	0.001	7.6	0.002	12.6	0.002	17.3
Export demand for sugar (bil. tonnes)	0.004	17.3	0.009	33.8	0.015	57.1

* A negative value denotes an inward shift.
Source: own calculations

The sizable changes (that must have occurred in combination in order to generate the surge in ethanol and sugar market prices from their 2010/11 levels) reported in Table 2 explain why the model developed earlier fails to approximate the 2011/12 outcome when only changes in Brazilian biofuel policies and technological parameters are considered.

This can better be seen in Table 3 where we decompose the observed change in Brazilian market prices between the 2010/11 (first column) and 2011/12 (second column) marketing years. The third column in Table 3 gives estimates of what the market prices would have been, had only the exogenous demand and supply shifts occurred (in combination) and policies been held at their 2010/11 levels. The magnitudes of the exogenous shocks correspond to those pertaining to the medium elasticity scenario in Table 2.

Table 3. Decomposition of a Change in Brazilian Market Prices between 2010/11 and 2011/12*

		Actual 2010/11	Actual 2011/12	2011/12 if market curves shifts only**	Observed price change	Change due to shifts	% of price change due to shifts in observed price change
Price of anhydrous ethanol	$/liter	1.18	1.42	1.43	0.24	0.25	101
Fuel price	$/liter	2.47	2.66	2.53	0.20	0.06	31
Market price of hydrous ethanol	$/liter	0.96	1.19	1.20	0.23	0.23	102
Consumer price of hydrous ethanol	$/liter	1.54	1.88	1.77	0.34	0.23	69
Price of sugarcane	$/tonne	56.11	67.83	73.69	11.72	17.58	150
Price of sugar	$/tonne	700.93	884.00	816.63	183.07	115.70	63

* These simulations assume market shocks (shifts) whose magnitudes correspond to the medium elasticity scenario in Table 2.
** Policies are held at their 2010/11 levels.
Source: calculated

In the fourth column, we compute the observed price change as the difference between the second and first column. The price changes due to the exogenous shifts only (fifth column) are given by the difference between the third and first column. Finally, the share of the price change attributable to the shifts in the total observed price change is equal to the ratio of the values in the fifth and fourth columns.

The fact that half of the values in the last column of Table 3 are more than 100 percent indicates that there are considerable market interaction effects not only between Brazilian policies, but also between the policies and exogenous market changes. For example, if biofuel policies had not changed between 2010/11 and 2011/12 and only structural market changes had occurred, we would have observed an even a greater increase in the ethanol price.

While Table 2 reports final shifts in market demand and supply curves that reflect all changes in the domestic Brazilian biofuel policy as well as changes in the rest of the world, from a policy analysis point of view, it is important to analyze the market effects of a change in a biofuel policy while assuming that all other factors, such as income growth or weather, are unchanged. But before we do so, let us model the endogenous shift in demand between E100 and fuel that is generated by a change in the parity gap between E100 and fuel prices when market changes occur.

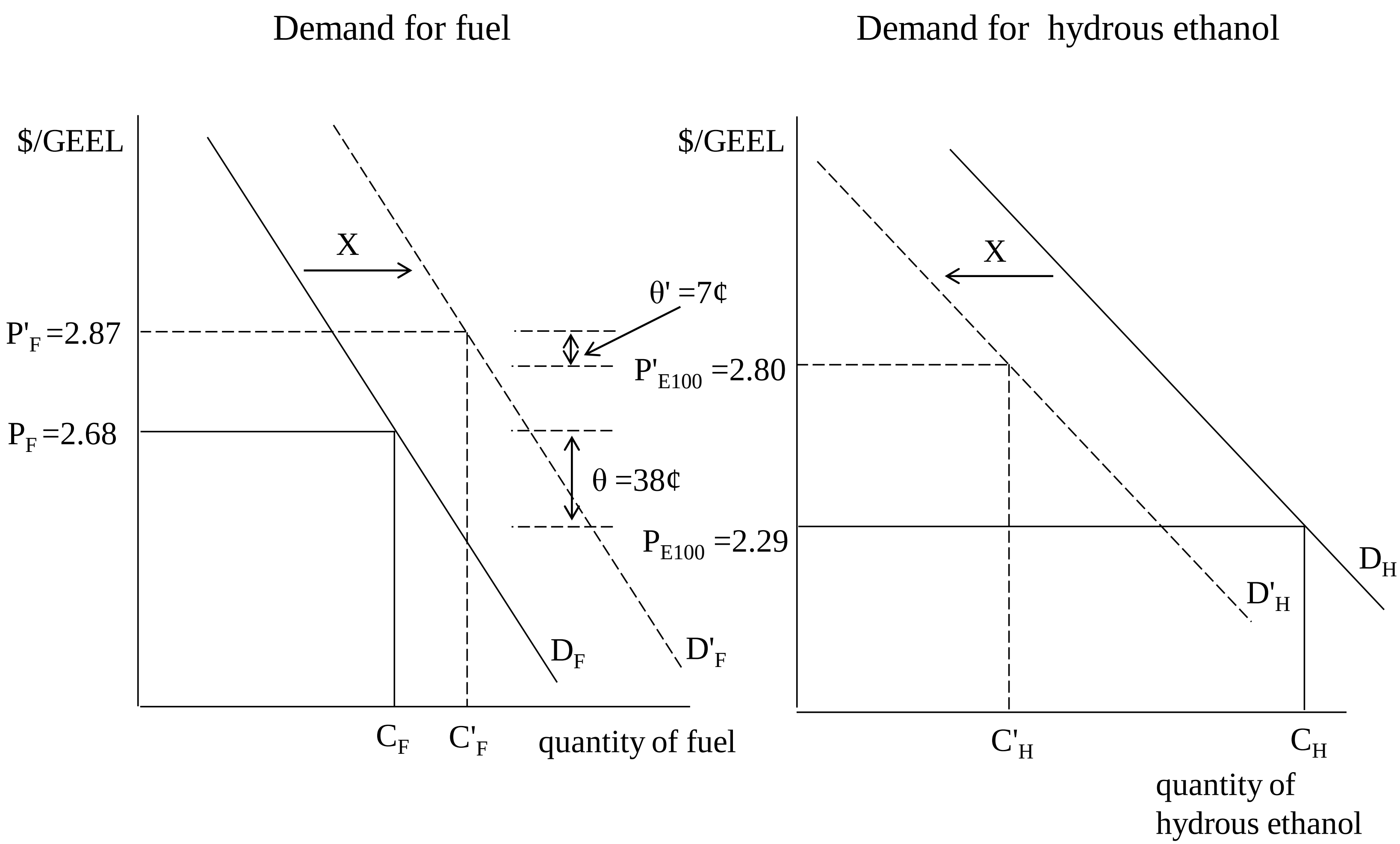
4. Modeling the Shift in Demand Curves for E100 versus Fuel

Because a change in the biofuel policy (e.g., an increase in the blend mandate or a reduction in the tax on gasoline), will, among other things, affect the relative price of the fuel blend and hydrous ethanol, the composition of fuels consumed will change accordingly. When the price gap (in energy equivalent) between fuel and E100 narrows, some flex cars owners who previously used hydrous ethanol (because at previous prices it was worth traveling to the nearest E100 pump station), will find it profitable to switch to the blended fuel.[51] In this case, the demand for fuel (measured in GEELs) shifts out by exactly the same amount as the demand for E100 shifts in, keeping the total consumption of fuel and E100 unchanged. This is shown in Figure 7 which uses actual prices for the 2010/11 and 2011/12 marketing years (the latter marked by the prime). The horizontal shift *X* does not reflect reality, however, since we are unrealistically assuming here that a change in the biofuel policy is the only driver of the demand shift.

In 2010/11, the price gap between fuel and E100 was 39¢/GEEL (= 2.68 - 2.29). Suppose that a change in all biofuel policies (i.e., an increase in the mandate, change in fuels taxes, and manipulation of the gasoline price) resulted in a rise in fuel and E100 consumer prices to \$2.88/GEEL and \$2.80/GEEL, respectively, reducing the price gap to 8¢/GEEL. As the relative

[51] Note that this is only possible for flex cars, as regular fuel (non-flex) vehicles are not able to run on E100.

Figure 7. Symmetrical Shifts in Demand for Fuel and Hydrous Ethanol



price changed in favor of fuel, demand for fuel shifts out to D'_F, while that for E100 shifts in to D'_H.

The magnitude of the shift X depends on the price gap θ: the bigger the gap, the bigger the shift. Let $X(\theta)$ be a function characterizing the behavior of flex car owners when the price gap, $\theta = P_F - P_{E100}$, changes. We assume that $X(\cdot)$ is at least once continuously differentiable and satisfies $X' = dX/d\theta > 0$. We also assume that at any point in time the owners of flex cars are sorted according to their propensity to switch between blend fuel and hydrous ethanol, depending on the relative prices of the two fuels. As the price gap widens, more flex car owners who currently consume fuel will find it preferable to switch to E100.

The model defined by equations (1) to (9) can readily be extended to incorporate the endogenous demand shift by specifying the demand curves for the fuel blend, D_F, and for E100, D_H, as follows[52]

$$D_F = f(P_F) - X(\theta) \tag{10}$$

$$D_H = g(P_{E100}) + X(\theta) \tag{11}$$

The functions $f(\cdot)$ and $g(\cdot)$ denote Marshallian demand functions for blend fuel and E100, respectively, and satisfy $f' = df/dP_F < 0$ and $g' = dg/dP_{E100} < 0$. The Marshallian demand curves shift horizontally by distance X whenever there is a change in the parity gap θ. Because the shift occurs only when the price gap changes, we must have $X(\theta_0) = 0$, where θ_0 denotes the price gap in the baseline (when the policies do not change and the existence of any price gap has been internalized). This point of the X function is very important as it determines the parity gap's

[52] Note that if the price gap decreases relative to the baseline, then the term $X(\theta) = 0$ becomes negative and the fuel demand curve shifts out, while that for E100 shifts in.

position on the horizontal axis. Figure 8 depicts a family of logistic curves that satisfy the properties (continuity, differentiability, and monotonicity) imposed on the function X.

5. Comparative Statics Results

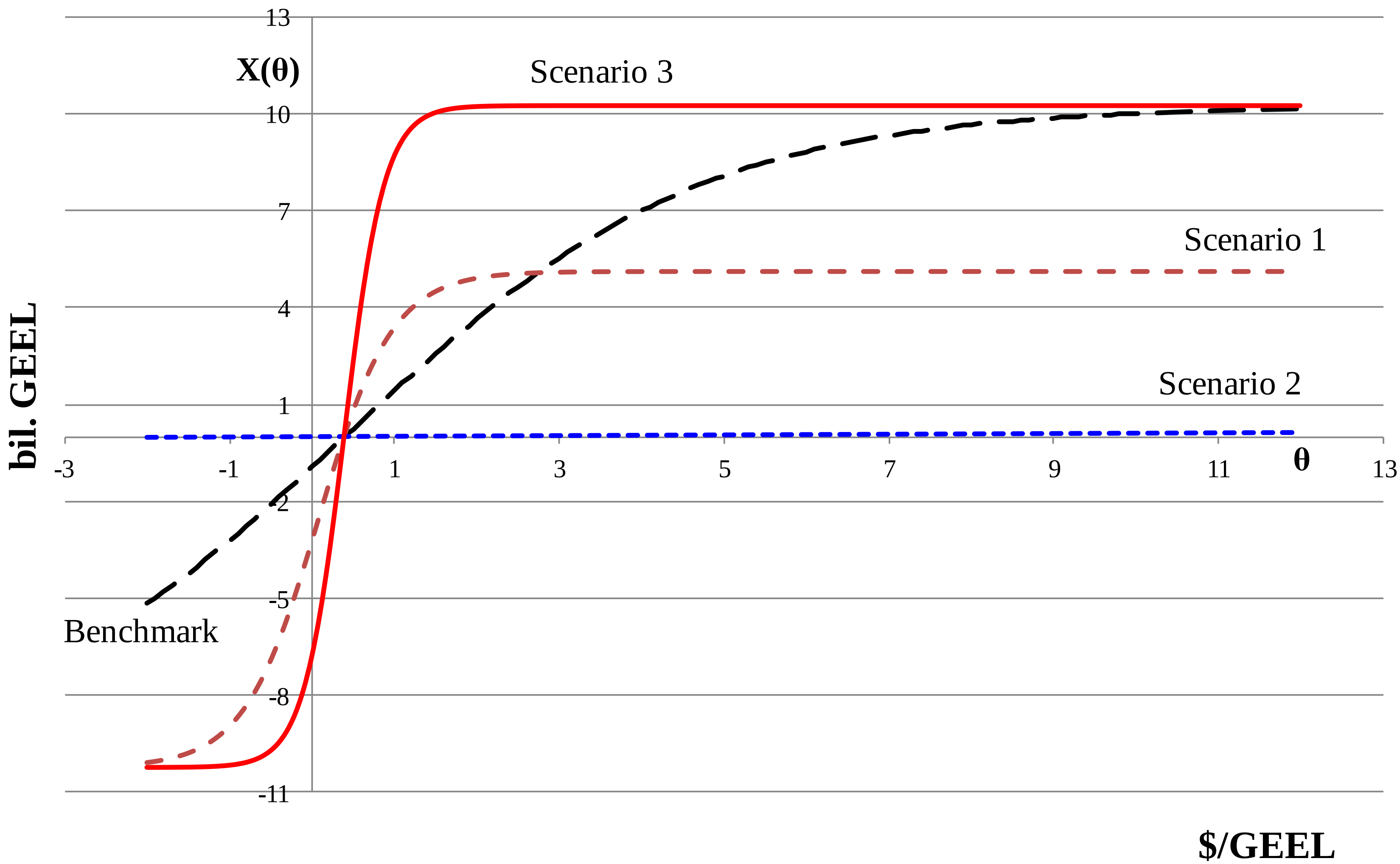
Equations (2) through (11) plus the definition $\theta = P_F - P_{E100}$ constitute a market equilibrium whose comparative statics results are presented in Appendix 1 and summarized in Table 4. In general, a change in a policy (i.e., mandate, gasoline price, gasoline tax, anhydrous or hydrous ethanol tax) has an ambiguous impact on market prices. The sign of most comparative statics results depends on the sign of the following expression

$$\frac{\alpha f'}{\phi_A} + \left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right) X' \equiv \frac{\eta_f \alpha f}{\phi_A P_F} + \left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right) \frac{dX}{d\theta} \tag{12}$$

where the slope of the fuel demand curve, f', has been expressed by means of the elasticity, η_f, of the Marshallian fuel demand. Intuitively, the right-hand side of expression (12) represents two simultaneously occurring effects. First, a change in any policy affects the price of fuel, which in turn results in a change in the quantity of fuel demanded; this is the shift along the fuel demand curve and is represented by the term f'. Second, a change in the fuel price P_F – combined with a change in the consumer price for hydrous ethanol – alters the price gap which affects flex cars owners' purchasing decision and so the demand curves for fuel and hydrous ethanol shift in opposite directions. The magnitude of the shift is represented by the term $dX/d\theta$.

The first term on the right side of identity (12) is unambiguously negative while the second term is negative only if $\alpha > \phi_A / \phi_H$. Using the observed parameters values for 2010/11 and 2011/12 marketing years, the second term is negative only for $\alpha > 0.96$; this means the Brazilian ethanol mandate would have to be at least 96 percent for the value on the right-hand side of equation identity (12) to be negative. We therefore do not consider this possibility further.

Figure 8. Logistic Curves for an Endogenous Demand Shift under Various Scenarios



The probability of the expression in (12) being negative increases with a higher elasticity of the fuel demand, higher blend mandate, and smaller sensitivity of flex car owners to the change in the price gap (represented by the term $dX/d\theta$). However, fuel demand is empirically found to be relatively price inelastic, and the observed blend mandate is around 25 percent. This suggests that the expression in (12) is very likely to be positive in reality (and we find that it is so in our empirical model). This is best seen if we assume an extreme case of perfectly inelastic fuel demand, that is, $\eta_f = 0$, in which case the expression is (almost surely) positive. In our further analysis, we therefore use the following assumption

Assumption 1: $\frac{\alpha f'}{\phi_A} + \left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right) X' > 0$.

Given Assumption 1, an exogenous increase in the gasoline price unambiguously results in an increase in all analyzed prices (Table 4). The intuition behind this result is that a higher gasoline price necessitates a higher price of fuel (gasoline plus anhydrous ethanol) paid by the consumers. This gives a cost advantage to hydrous ethanol whose demand shifts out (by the same amount by which the demand for fuel shifts in), thus increasing the market price and consumer price of hydrous ethanol. But as equation (5) shows, the market prices of anhydrous and hydrous ethanol are linked on the supply side, which gives rise to a higher price of anhydrous ethanol. Owing to the higher competition for the feedstock, the prices of sugarcane and sugar increase.

Table 4. Effect of a Change in a Policy on Market Prices[a]

Increase in…	Market price of ethanol[b]	Consumer price of E100	Price of fuel	Gap in Fuel & E100 price
Gasoline price/tax[c]	+	+	+	+
Tax on anhydrous ethanol	+	+	+	+
Tax on hydrous ethanol	–	+/– [+][d]	–	–
Mandate	+/– [+]	+/– [+]	+/– [–]	+/– [–]

[a] The unambiguous signs are conditional on *Assumption 1*.
[b] We do not distinguish between anhydrous and hydrous ethanol prices nor report the effects on sugar and sugarcane prices as all four prices move in the same direction.

[c] These effects are equal not only in sign, but also in magnitude.
[d] Signs in square brackets refer to our empirical results.
Source: Appendix 1.

The tax on gasoline has identical (both in magnitude and in sign) market effects as the gasoline price. The directional effects of a higher tax on anhydrous ethanol (or equivalently a lower tax exemption) on market prices are also the same as for the gasoline price. The explanation for the signs follows the same logic as above— a higher tax on anhydrous ethanol increases the consumer price of fuel.

However, the price effects of an increase in the tax on hydrous ethanol (or equivalently a reduction in a tax exemption) exhibit an opposite pattern. The tax drives a wedge between the consumer price and market price of hydrous ethanol. As this wedge grows larger, the market price of hydrous ethanol decreases. But because on the supply side it is linked to the anhydrous ethanol price, the latter decreases, too, making the blending of fuel less expensive for the blenders; hence, the fuel price decreases. Weaker competition for sugarcane pushes its price and production down. However, the reduction in sugarcane use due to a decreased need for ethanol more than offsets the reduction in sugarcane production, thus diverting more feedstock to sugar production. As the supply of sugar increases, its market price falls.

Interestingly, a higher tax has an ambiguous effect on the consumer price of hydrous ethanol. Whether this price will increase or decrease depends on the relative magnitudes of the inward shifts in the demand and supply curves for hydrous ethanol. The demand curve shifts in because of a change in the relative prices (in favor of fuel), and the supply curve contracts because a lower market price of hydrous ethanol makes this product less profitable to producers, who subsequently divert sugarcane to sugar production.

Finally, we note that Assumption 1 is not sufficient to draw unequivocal conclusions about the effect of a higher mandate on the market equilibrium (although, as we show later, a higher mandate empirically results in a higher ethanol price). This ambiguity contrasts with the prediction of the model by de Gorter and Just (2009), where a higher mandate with perfectly elastic gasoline supply unambiguously results in a higher ethanol price. The effect of a mandate on the ethanol price differs between their model and ours since they study only one ethanol demand curve (corn ethanol) while we analyze two competing demand curves for ethanol uses.

6. Data and Calibration

The substantial proportion of hydrous ethanol in total ethanol consumption in Brazil (71 and 60 percent in 2010/11 and 2011/12, respectively) necessitates a consistent measurement of fuel-related quantities and prices in energy-equivalent terms (i.e., according to vehicle kilometers traveled). As described above, hydrous ethanol is typically sold as E100 (i.e., 100 percent ethanol) to owners of flex cars. The empirical evidence suggests that owners of flex cars buy fuel according to the price per kilometer traveled, not per liter bought. To that end, all prices and quantities related to anhydrous and hydrous ethanol as well as fuel (the blend of anhydrous ethanol and gasoline) are expressed in gasoline energy-equivalent liters (Appendix 4).[53]

One liter of anhydrous or hydrous ethanol yields only 67 percent of kilometers traveled relative to one liter of gasoline. Because anhydrous ethanol cannot be used in its pure form, the number of kilometers traveled per liter of fuel is equal to the weighted average of kilometers per liter of anhydrous ethanol (if, hypothetically, in the pure form) and gasoline. The result will thus depend on the share of the anhydrous ethanol in the blend. Given the 2010/11 and 2011/12 mandate level the relative kilometrage of fuel is equal to 0.92 in both years.

[53] Sources of the data used and formulas for other variables' calculation are listed in Appendix 4.

The yield of sugar, anhydrous and hydrous ethanol from one tonne of sugarcane is not constant but depends largely on the quality of the cane and the way the juice is extracted; the quality in turn depends heavily on the weather in a given year. The data indicate that the weather conditions in 2011/12 adversely affected the yields of sugar, anhydrous and hydrous ethanol relative to 2010/11: output totaled 130kg, 68.6 liters, and 71.6 liters, respectively, in 2011/12 *vs* 133kg, 71.7 liters, and 75.0 liters, respectively, in 2010/11.

The state-of-the-art production plants that process the sugarcane into sugar are able to make use of the sugar's by-product, molasses. Currently, as many as 9.25 liters of ethanol (anhydrous and hydrous combined) can be extracted from the molasses obtained from one tonne of sugarcane. Because the proportion of both ethanol types produced from molasses varies among individual producers, we assume that the ratio of anhydrous and hydrous ethanol produced is the same as the observed ratio of these ethanol types in overall ethanol production. Thus, for example, in 2010/11, the amount of anhydrous ethanol from molasses per tonne of sugarcane is equal to $0.29*9.25 = 2.69$ liters, and that of hydrous ethanol is equal to $9.25 – 2.69 = 6.56$ liters.

Using bagasse for electricity cogeneration significantly improves the economics of all products derived from sugarcane. To illustrate this, the Brazilian Sugarcane Industry Association (UNICA) reports that one tonne of sugarcane produces 250 kilograms of bagasse worth 85.6 kWh of electricity.[54] The excess supply of electricity not used in the plant, approximately 63 kWh, is currently sold on the grid for about $R100/MWh (although the price varies).[55] This price

[54] http://cavalierecapital.com/yahoo_site_admin/assets/docs/Ethanol_A_sustainable_alternative_for_transport.51114446.pdf

[55] This corresponds to approximately $50/MWh.

needs to be adjusted for the losses of electricity during distribution, however. (It is estimated that the above price would be reduced by as much as 25 percent).

In our empirical simulations, we model three biofuel policies: an ethanol mandate, a tax exemption on anhydrous ethanol (i.e., the difference between the tax levied on gasoline and anhydrous ethanol), and fuel taxes. We calibrate our model to the observed mandate as represented by the actual share of anhydrous ethanol in total fuel consumption, that is, 24.6 and 23.1 percent for 2010/11 and 2011/12, respectively. The system of Brazilian fuel taxes is complex. Appendix 3 presents calculations of the individual taxes on gasoline and the two types of ethanol.

Our (non-linear) demand and supply curves are assumed to have constant price elasticities. The central estimates of these elasticities come from recent studies analyzing the Brazilian market. In particular, the sugarcane supply elasticity is assumed to be 0.5 (Schmitz et al, 2003), reflecting the fact that sugarcane is a perennial and its replanting requires significant investments. The elasticity of the domestic demand for sugar is assumed to be -0.75 (de Freitas and Kaneko 2011) while the assumed elasticity of export demand for sugar is substantially higher, -2. We use Menezes et al. (2008)'s estimated elasticity of demand for fuel: -0.23. This value is close to the estimate (for the Unites States) reported by Hamilton (2009), and also close to the medium/long run meta-analysis estimate by Havránek (2011). The assumed demand elasticity for hydrous ethanol is more elastic: -0.68 (Menezes et al. 2008); this is not surprising, because hydrous ethanol can only be used in flex cars whose owners can easily change their fuel blend proportion according to relative prices.

We compute the price of fuel as the weighted average of anhydrous and gasoline prices adjusted for their respective taxes. The weights are equal to the shares of ethanol and gasoline in the final fuel blend. The observed fuel price is higher than our computed value, but we attribute the difference to the marketing margin and treat the margin as a constant. The observed consumer price of hydrous ethanol is also greater than our calculated value, and we treat this as a constant marketing margin as well.

The gap between the price of fuel and hydrous ethanol was \$0.39/GEEL in 2010/11 but dropped to \$0.08/GEEL in 2011/12. Given the relatively large gap in 2010/11, one can hypothesize that the owners of flex cars were less sensitive to a change in the relative fuel price than they would be in 2011/12. This implies that any shock in the price gap in 2010/11 would have been more likely to induce a smaller shift in the demand for hydrous ethanol than in 2011/12.

The sugarcane production is used for sugar and anhydrous and hydrous ethanol. The production of both anhydrous and hydrous ethanol exceeds their domestic use. The difference is due to trade and industrial use of the ethanol. We assume that this part of ethanol production is exogenous, that is, the biofuel policies do not affect those markets. Brazil exports about two thirds of its sugar production.

7. An Empirical Illustration

The Shift Function

We use a logistic function of the form

$$X(\theta) = \frac{A}{1 + Be^{-C\theta}} + D \tag{13}$$

to model the propensity of flex cars owners to switch between consumption of fuel and E100. Parameters *A* and *D* relate to the asymptotes of the logistic function and parameters *B* and *D* relate to its shape. (For a discussion of these parameters and their calibration, see Appendix 2). This function is increasing in its argument, meaning that a higher gap between the consumer prices of fuel and hydrous ethanol leads to a greater shift-out of the demand for hydrous ethanol (coupled with an opposite shift-in of the demand for fuel).

We set the lower asymptote of function (13) to be the negative of consumption of hydrous ethanol in the baseline, because the maximum reduction in the demand for hydrous ethanol would occur if all flex cars using hydrous ethanol in the baseline switched to the fuel blend. The upper asymptote is harder to pin down. Its level depends on how much fuel the flex cars consume in the baseline, and this information is not readily available. We therefore perform a sensitivity analysis with respect to the upper asymptote, as well as to the curvature of the function *X*. Parameter values under various scenarios are summarized in Table 5.

Table 5. Summary of Parameters of the Logistic Function used in Simulations

	Benchmark	Scenario 1	Scenario 2	Scenario 3
Upper asymptote	10.24	5.12	12.28	10.24
Lower asymptote	-10.24	-10.24	-10.24	-10.24
A	20.48	15.36	22.52	20.48
B	1.20	1.20	1.20	5.00
C*	0.46	2.23	0.00	4.10
D	-10.24	-10.24	-10.24	-10.24
Price gap (θ)	0.39	0.39	0.39	0.39

* calibrated value
Source: own calculations

In the benchmark, we assume that the upper asymptote is equal to the negative of the lower asymptote (-10.24 bil. GEELs), meaning that half of flex cars consumes hydrous ethanol and the other half consumes fuel in the baseline. The larger the gap between consumer prices of fuel and hydrous ethanol at a given point in time, the less sensitive flex cars owners are to changes in this gap. Consider, for instance, the actual price gap of $0.39/GEEL observed in 2010/11. In this case, a small perturbation in the price differential is likely to result in a small change in the proportion of fuel and hydrous ethanol use because flex car owners are already "inclined" to use hydrous ethanol. Contrast this with the price differential of $0.08/GEEL observed in 2011/12. It is reasonable to assume that the inclination to hydrous ethanol is not as strong now as in the previous case, hence a greater sensitivity to a change in the price gap.

To reflect the arguments above, we set the value of the shape parameter *B* to be 1.2 in the benchmark and Scenarios 1 and 2, but set it much higher (*B* =5) in Scenario 3.[56] The parameter *C* is calibrated (Appendix 2) to ensure that given the values of other parameters, the following condition holds: $X(\theta_0) = 0$. The logistic curve corresponding to the benchmark specification is depicted in Figure 8.

In Scenario 1, we set the upper asymptote to one half of its benchmark level (5.12 bil. GEELs), while in Scenario 2 we set it to 12.28 bil. GEEL, which is the highest possible value that is consistent with our assumptions on the signs of other parameters.[57] As shown in Figure 8, under this scenario, flex cars owners hardly respond to the change in the price gap. The opposite is true for Scenario 3 (*B* = 5), where a small deviation from the current price gap makes many flex cars switch to an alternative fuel.

Policy Simulations

We run a battery of simulations to analyze the impacts of individual biofuel policies and market shocks quantitatively. All price changes possess the predicted signs presented in Table 4. The first set of simulations (columns denoted by B = 1.2 in Table 6 and 7) assumes that the behavior of owners of flex cars is described by the benchmark logistic curve in Figure 8, whereas the second set (columns denoted by B = 5) uses the Scenario 3 logistic curve to investigate how the

[56] The values for the shape parameter *B* were arbitrarily chosen to illustrate the point that the sensitivity of flex car owners to the observed price gap can differ depending on the size of the gap. The relative size of the two values of the shape parameter matters more that their levels. But it should be noted that the choice of this parameters is not completely arbitrary because if the shape parameters is less than unity, the logistic curve becomes decreasing, which runs afoul of our assumption about the monotonicity of this curve.

[57] If the upper asymptote were higher than 12.2 bil. GEELs, the logistic function would be decreasing, thus contradicting our assumption that the bigger the price gap, the bigger the shift. This happens because by requiring that $X(\theta_0) = 0$, we are imposing structure on the logistic function that does not allow for any choice of the upper asymptote.

market outcomes differ if flex cars owners are very sensitive to a change in the fuel price gap. The vector of baseline policies (in effect in the 2010/11 marketing year) consists of the volumetric blend mandate $\alpha = 0.246$, the tax on gasoline t_G = \$1.28/liter, the tax on anhydrous ethanol t_A = \$0.048/liter, the tax on hydrous ethanol t_H = \$0.262/liter, and the gasoline price P_G = \$1.05/liter.

Table 6. Policy Simulations Results*

	Baseline	Difference relative to baseline: 28 ¢ reduction in gasoline tax**		5 percentage point reduction in mandate		Parity between anhydrous and gasoline tax		Parity between hydrous and fuel taxes		No mandate, and all taxes at parity	
		B = 1.2	B = 5	B = 1.2	B = 5	B = 1.2	B = 5	B = 1.2	B = 5	B = 1.2	B = 5
Fuel price (\$/liter)	2.47	-0.21	-0.23	0.05	0.05	0.20	0.22	-0.02	-0.05	0.27	0.08
Market price of anhydrous ethanol (\$/liter)	1.18	-0.01	-0.06	-0.03	-0.02	0.01	0.06	-0.07	-0.19	-0.21	-0.18
Market price of E100 (\$/liter)	0.96	-0.01	-0.06	-0.03	-0.01	0.01	0.06	-0.07	-0.18	-0.20	-0.17
Consumer price of E100 (\$/liter)	1.54	-0.01	-0.06	-0.03	-0.01	0.01	0.06	0.38	0.27	0.40	0.42
Price of sugarcane (\$/tonne)	56.11	-0.59	-4.50	-1.96	-1.12	0.58	4.50	-5.26	-13.56	-14.73	-13.03
Price of sugar (\$/tonne)	700.93	-3.88	-29.64	-12.93	-7.39	3.83	29.59	-34.60	-89.26	-96.95	-85.78

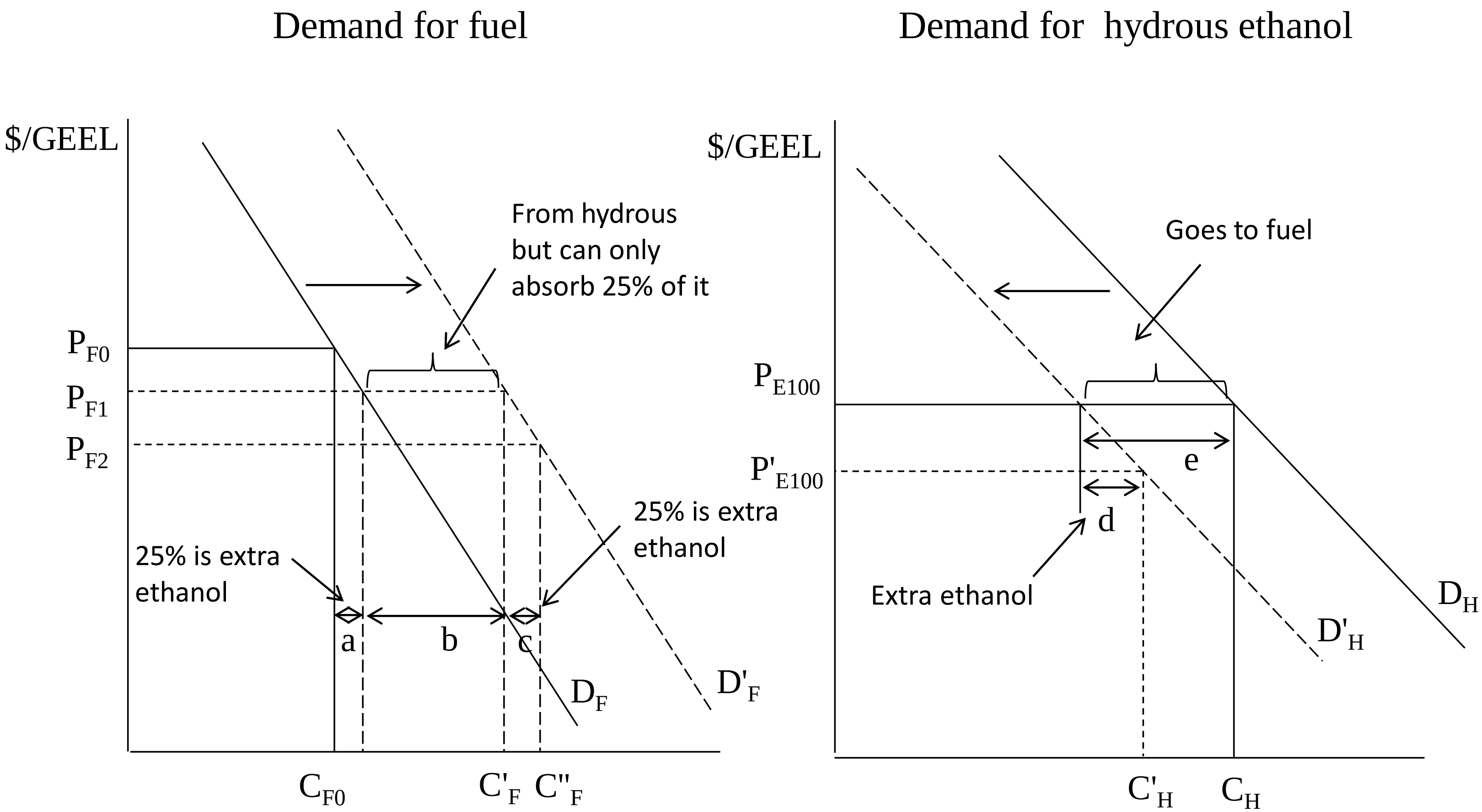
* Mandate binding in all simulations except the last one.
** Or the same reduction in gasoline price.
B = 1.2 means that flex cars owners are less sensitive, and B = 5 that they are very sensitive to a change in the fuel price gap.
Source: own calculations

The first policy scenario presented in Table 6 models a recent 28 cent per liter reduction in the gasoline tax (assuming it occurred in the 2010/11 marketing year); ethanol prices decline by 1 cent as a result. The comparative statics results presented in Appendix 1 show that a decrease in the gasoline tax has identical effects – in both sign and magnitude –as a reduction in the gasoline price. This makes our exposition easier because the gasoline price in Brazil is believed to be below its world market counterpart by approximately the same amount as the recent reduction in the gasoline tax. Thus, the results for the first scenario are not only informative of the magnitudes of the market effects of a gasoline tax shock, but also of the effects of exogenously pegging the gasoline price in Brazil below the world price.

The instantaneous effect of a lower gasoline tax is a reduction in the price of fuel from P_{F0} to P_{F1} in Figure 9. This results in an increase in the consumption of fuel by the distance *a*, 25 percent of which is anhydrous ethanol when the mandate is 25 percent (i.e., with E25). With this decline in the fuel price, the parity gap between fuel and E100 prices declines to $P_{F1} – P_{E100}$ and some E100 consumers switch to fuel consumption. As a result, the hydrous demand curve shifts in by the same amount (distance *e*) as the fuel demand curve shifts out (distance *b*), since the distances are measured in gasoline energy-equivalent liters.

The reduced demand for hydrous ethanol results in a new demand curve D'_H, with a decline in the price of hydrous ethanol to P'_{E100} , thus partially offsetting the decline in hydrous ethanol consumption by distance *d* to yield a net reduction in hydrous ethanol consumption of distance $e – d$. If the fuel price stayed at P_{F1}, resulting fuel consumption would correspond to C'_F. But because the hydrous and anhydrous ethanol prices are linked on the supply side, the anhydrous ethanol price falls, resulting in a further reduction in the fuel price, denoted by P_{F2}. Of the additional fuel consumption associated with this price decrease, 25 percent is anhydrous ethanol. In total, a reduction in the gasoline tax brings about an increase in fuel consumption of $a + b + c$, and hence a higher need for anhydrous ethanol of 0.25 x ($a + b + c$). On the other hand, the net decrease in the use of hydrous ethanol is $e – d$. Therefore, if 0.25 x ($a + b + c$) < $e – d$,

Figure 9. Effects of a Decrease in the Gasoline Tax



then the total use of ethanol declines, resulting in a decrease in both hydrous and anhydrous ethanol prices.

The effect of the government arbitrarily reducing the gasoline price below the world price follows the same set of arguments as the reduction in the gasoline tax, while an increase in the tax exemption for hydrous ethanol (equivalent to a decrease in the tax) has the reverse logic of Figure 9 where the demand for hydrous ethanol shifts out first to D'_H.

In the second scenario, we analyze what would happen if the 2010/11 mandate decreased by 5 percentage points. Currently, the mandate can range between 18 and 25 percent in Brazil. Our results reported in Table 6 suggest that the sensitivity of flex cars owners (proxied by the curvature of the shift function) has a minimal effect on market outcomes. For example, while the market price of hydrous ethanol decreases by 3 cents (relative to the baseline) when the mandate is reduced and flex cars owners are less sensitive, it decreases by 2 cents for the same policy change with more sensitive flex car owners.

Notice also that a reduction in the mandate has associated with it an increase in the fuel price by 5 cents. This illustrates our earlier comparative statics result that an exogenous change in the blend mandate, *given a perfectly elastic supply of gasoline*, can have opposite effects in different market environments. To reiterate, in a market with only one demand curve for ethanol, like in the United States, a lower mandate would unambiguously result in a lower fuel price; this might, however, not be the case in an environment with two competing demand for ethanol (as we show in Table 6).[58] In sum, the mandate in Brazil operates very differently from the traditional blend mandate model.

[58] The blend mandate model by de Gorter and Just (2009) predicts that a higher gasoline price (given a perfectly elastic gasoline supply curve) unequivocally reduces the ethanol price, while Lapan and Moschini's (2012) model (with a fixed consumption mandate) would predict no change in ethanol price. Moreover, both models predict that a higher mandate results in a higher fuel price (provided the gasoline price is fixed).

In Brazil, anhydrous ethanol enjoys a significant tax exemption *vis-à-vis* gasoline (as much as $1.21/GEEL). But fuel consumers benefit from it only to the extent that it lowers the final fuel price which they face (since anhydrous ethanol cannot be purchased in its pure form and is always blended with gasoline). If anhydrous ethanol were taxed on parity with gasoline (so that the tax exemption was eliminated), all market prices would increase, although only marginally—for instance, ethanol prices are predicted to rise by 1 cent (see third scenario in Table 6). This result implies that ethanol producers would be better off with a higher tax on anhydrous ethanol, since they are being implicitly taxed by the existing generous anhydrous tax exemption.

On the other hand, when the tax on hydrous ethanol is raised to obtain parity between the tax-inclusive hydrous ethanol and fuel prices (with the gasoline and anhydrous ethanol taxes held at their baseline levels), ethanol prices decline by R$0.07 per liter, making the ethanol producers worse-off. This occurs because the tax drives a wedge between the consumer and producer price of hydrous ethanol, pushing the latter down.

The last scenario presented in Table 6 analyzes the effects of the elimination of the blend mandate and all tax exemptions (i.e., the tax on anhydrous ethanol is on parity with that on gasoline while the tax on hydrous ethanol is on parity with the fuel tax, where the fuel tax is given by the weighted average of gasoline and anhydrous taxes). A significantly higher anhydrous price makes the marginal cost to fuel blenders rise, resulting in an increase in the fuel price. A higher consumer price for hydrous ethanol leads to a net decrease in the demand for hydrous ethanol, resulting in lower ethanol production, and thus its lower market price.

The sum total effect of eliminating the Brazilian ethanol mandate and tax exemptions (with the gasoline price and taxes held constant) is to reduce hydrous ethanol prices by 21 percent (= – 0.20/0.96 [x100%]). Other recent research (Drabik 2011) finds a comparable effect of eliminating U.S. ethanol policies for the same time period (a 24 percent reduction in U.S. ethanol prices), although ethanol prices are higher in Brazil and U.S. ethanol consumption is more than twice that of Brazil.

Unlike in the United States, where the mandate always acts as a lower bound on the ethanol price (i.e., it determines the minimum price), the mandate in Brazil may be either a lower or an upper bound. The latter may occur, for example, if sugar demand is low and sugarcane supplies are plentiful. In that case, the removal of the mandate would increase the ethanol price.

Table 7 presents results for simulations where the Brazilian market experiences a negative sugarcane supply shock , a positive shock to the demand for fuel (with corresponding negative shock to demand for hydrous ethanol), and a positive demand shock for sugar.

Table 7. Market Shocks Simulations Results*

		Difference relative to baseline					
	Baseline	Reduction in supply of sugarcane**		Increase in demand for fuel & reduction in demand for E100 ***		Increase in demand for sugar ****	
		B = 1.2	B = 5	B = 1.2	B = 5	B = 1.2	B = 5
Fuel price ($/liter)	2.47	0.04	0.03	-0.01	0.00	0.02	0.01
Market price of anhydrous ethanol ($/liter)	1.18	0.15	0.10	-0.02	-0.02	0.09	0.06
Market price of E100 ($/liter)	0.96	0.15	0.10	-0.02	-0.01	0.08	0.06
Consumer price of E100 ($/liter)	1.54	0.15	0.10	-0.02	-0.01	0.08	0.06
Price of sugarcane ($/tonne)	56.11	11.07	7.47	-1.58	-1.11	6.29	4.29
Price of sugar ($/tonne)	700.93	72.88	49.14	-10.42	-7.31	41.38	28.23

* Mandate binding in all simulations.

** Reduction of 18.3%.

*** Increase of 22.8%; reduction of 20.6%.

**** Increase in domestic demand of 12.6% and increase in export demand of 33.8%.

B = 1.2 means that flex cars owners are less sensitive, and B = 5 that they are very sensitive to a change in the fuel price gap.

Source: own calculations

The magnitudes of the shocks correspond to the medium scenario values presented in Table 2. Both the "increase in demand for sugar" and "reduction in supply of sugar" scenarios yield the same qualitative conclusions: as the price of sugarcane increases, making production of anhydrous and hydrous ethanol and sugar more expensive, the market prices of these commodities rise. A higher market price of anhydrous ethanol increases the marginal cost for fuel blenders, which increases the consumer price of fuel.

8. Conclusions

Dramatic changes have occurred recently in Brazilian ethanol and sugar markets. This paper presents a general economic model of the Brazilian sugar/ethanol nexus from the processing of sugarcane, which determines the world price of sugar and the Brazilian market price for ethanol. Domestic ethanol demand is depicted in two demand curves – one for fuel (a mixture of anhydrous ethanol and gasoline) and the other for hydrous ethanol (E100). We incorporate an endogenous switching model for E100 consumers as they respond to changes in the relative prices of E100 and fuel. On the supply side, we incorporate the economics of electricity production from bagasse, ethanol production from molasses (a by-product of sugar production), and we also incorporate the differential cost of producing hydrous and anhydrous ethanol, thereby keeping a specific price link between the two types of ethanol.

This paper has several key findings. Unlike biofuel mandates and tax exemptions elsewhere, Brazil's fuel-ethanol-sugar markets and fuel policies are unique in that each policy, in theory, has an ambiguous impact on the market price of ethanol and hence on sugarcane and sugar prices. The Brazilian market is complex with two competing demands for ethanol use, so any initial change in ethanol price due to a policy change can be offset by consumers' shifts in demand for E100 versus fuel. Furthermore, the sugarcane feedstock can be used to produce two competing products, sugar and ethanol, which give processors more flexibility. However, under plausible assumptions regarding the elasticity of the fuel demand curve and the responsiveness of flex car owners to changes in relative prices, we find that most of the policies analyzed have an unambiguous impact on ethanol prices.

Our empirical analysis shows there are two policies that seemingly help the ethanol industry but do otherwise in reality: a low gasoline tax and a high anhydrous tax exemption results in lower ethanol prices (unlike in the U.S. where lower gasoline tax will increase ethanol prices regardless and a lower gasoline price increases the ethanol price in the case of a binding blend mandate). On the other hand, as expected, higher mandates, gasoline prices, and tax exemptions for hydrous ethanol in Brazil means higher ethanol and sugar prices.

Eliminating Brazilian ethanol tax exemptions and mandates reduces ethanol prices by 21 percent in 2010-11, which is very similar to the estimated effects of U.S. ethanol policies by Drabik (2011) for the same time period. But the marginal changes in Brazilian policies on ethanol prices between 2010-11 and 2011-12 are shown in this paper to be relatively small both individually and collectively. We find that observed market changes can only be explained by outward shifts in fuel transportation and sugar export demand curves, and reduced sugarcane supply due to bad weather.

Although the hydrous ethanol tax exemption always increases ethanol prices (with or without the mandate), in principle it is very possible that the mandate in Brazil can also act as an upper bound on ethanol consumption (rather than a lower bound as is always the case in the United States), depending on the year and market circumstances. This outcome is more likely, *inter alia*, when sugar demand is low and sugarcane supplies are plentiful. In that case, the removal of the mandate will increase the ethanol price. The number of years in which this has happened in the past (if ever) and the extent to which ethanol prices would have risen with the elimination of the mandate awaits further research.

Appendix 1. Comparative Statics Results

Totally differentiating the system of equations (2) to (4) and (6) to (11) and recalling that

$\theta = P_F - P_{E100}$, we arrive at

$$
\begin{aligned}
&dP_{SC} = \phi_S dP_S + \delta_H dP_H + \delta_A dP_A \\
&dP_{SC} = \phi_H dP_H \\
&dP_{SC} = \phi_A dP_A \\
&dP_F = \left(P_A + t_A - P_G - t_G\right) d\alpha + \alpha dP_A + \alpha dt_A + \left(1-\alpha\right) dP_G + \left(1-\alpha\right) dt_G \\
&dP_{E100} = dP_H + dt_H \\
&S_{SC}\,' dP_{SC} = \left(1 - \frac{\delta_H}{\phi_H} - \frac{\delta_A}{\phi_A}\right) dC_{SC}^S + \frac{1}{\phi_H} dD_H + \frac{D_F}{\phi_A} d\alpha + \frac{\alpha}{\phi_A} dD_F \\
&\left(D_S^D\,' + D_S^W\,'\right) dP_S = \phi_S dC_{SC}^S \\
&d\theta = dP_F - dP_{E100} \\
&dD_F = f\,' dP_F - X\,' d\theta \\
&dD_H = g\,' dP_{E100} + X\,' d\theta
\end{aligned}
$$

where the prime (') denotes the derivative of a function with respect to its argument.

Using the Implicit Function Theorem, we obtain changes in the prices of interest with respect to a marginal change in a policy variable. To simplify the expressions to follow, we define

$$
Z = \phi_H \left[S_{SC}\,' - \left(\frac{g\,'}{\phi_H{}^2} + \frac{\alpha^2 f\,'}{\phi_A{}^2} \right) + \left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A} \right)^2 X\,' - \left(1 - \frac{\delta_H}{\phi_H} - \frac{\delta_A}{\phi_A} \right)^2 \frac{\left(D_S^D\,' + D_S^W\,'\right)}{\phi_S{}^2} \right] > 0
$$

The individual derivatives take the following forms:

$$
\begin{aligned}
&\frac{dP_H}{d\alpha} = \frac{dP_{E100}}{d\alpha} = \frac{\left(P_A + t_A - P_G - t_G\right)\left[\frac{\alpha f'}{\phi_A} + \left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right)X'\right] + \frac{D_F}{\phi_A}}{Z} \\
&\frac{dP_A}{d\alpha} = \frac{\phi_H}{\phi_A}\frac{dP_H}{d\alpha} \\
&\frac{dP_F}{d\alpha} = \frac{\alpha\phi_H}{\phi_A}\frac{dP_H}{d\alpha} + \left(P_A + t_A - P_G - t_G\right) \\
&\frac{d\theta}{d\alpha} = \left(P_A + t_A - P_G - t_G\right) - \phi_H\left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right)\frac{dP_H}{d\alpha} \\
&\frac{dP_{SC}}{d\alpha} = \phi_H\frac{dP_H}{d\alpha} \\
&\frac{dP_S}{d\alpha} = \frac{\phi_H}{\phi_S}\left(1 - \frac{\delta_H}{\phi_H} - \frac{\delta_A}{\phi_A}\right)\frac{dP_H}{d\alpha}
\end{aligned}
\qquad \text{(A1.1)}
$$

$$
\begin{aligned}
&\frac{dP_H}{dP_G} = \frac{dP_{E100}}{dP_G} = \frac{\left(1-\alpha\right)\left[\frac{\alpha f'}{\phi_A} + \left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right)X'\right]}{Z} \\
&\frac{dP_A}{dP_G} = \frac{\phi_H}{\phi_A}\frac{dP_H}{dP_G} \\
&\frac{dP_F}{dP_G} = \alpha\frac{\phi_H}{\phi_A}\frac{dP_H}{dP_G} + \left(1-\alpha\right) \\
&\frac{d\theta}{dP_G} = \left(1-\alpha\right) - \phi_H\left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right)\frac{dP_H}{dP_G} \\
&\frac{dP_{SC}}{dP_G} = \phi_H\frac{dP_H}{dP_G} \\
&\frac{dP_S}{dP_G} = \frac{\phi_H}{\phi_S}\left(1 - \frac{\delta_H}{\phi_H} - \frac{\delta_A}{\phi_A}\right)\frac{dP_H}{dP_G}
\end{aligned}
\qquad \text{(A1.2)}
$$

$$\frac{dP_H}{dt_G} = \frac{dP_{E100}}{dt_G} = \frac{\left(1-\alpha\right)\left[\dfrac{\alpha f'}{\phi_A} + \left(\dfrac{1}{\phi_H} - \dfrac{\alpha}{\phi_A}\right)X'\right]}{Z}$$

$$\frac{dP_A}{dt_G} = \frac{\phi_H}{\phi_A}\frac{dP_H}{dt_G}$$

$$\frac{dP_F}{dt_G} = \frac{\alpha\phi_H}{\phi_A}\frac{dP_H}{dt_G} + \left(1-\alpha\right) \tag{A1.3}$$

$$\frac{d\theta}{dt_G} = \left(1-\alpha\right) - \phi_H\left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right)\frac{dP_H}{dt_G}$$

$$\frac{dP_{SC}}{dt_G} = \phi_H\frac{dP_H}{dt_G}$$

$$\frac{dP_S}{dt_G} = \frac{\phi_H}{\phi_S}\left(1 - \frac{\delta_H}{\phi_H} - \frac{\delta_A}{\phi_A}\right)\frac{dP_H}{dt_G}$$

$$\frac{dP_H}{dt_A} = \frac{dP_{E100}}{dt_A} = \frac{\alpha\left[\dfrac{\alpha f'}{\phi_A} + \left(\dfrac{1}{\phi_H} - \dfrac{\alpha}{\phi_A}\right)X'\right]}{Z}$$

$$\frac{dP_A}{dt_A} = \frac{\phi_H}{\phi_A}\frac{dP_H}{dt_A}$$

$$\frac{dP_F}{dt_A} = \frac{\alpha\phi_H}{\phi_A}\frac{dP_H}{dt_A} + \alpha \tag{A1.4}$$

$$\frac{d\theta}{dt_A} = \alpha - \phi_H\left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right)\frac{dP_H}{dt_A}$$

$$\frac{dP_{SC}}{dt_A} = \phi_H\frac{dP_H}{dt_A}$$

$$\frac{dP_S}{dt_A} = \frac{\phi_H}{\phi_S}\left(1 - \frac{\delta_H}{\phi_H} - \frac{\delta_A}{\phi_A}\right)\frac{dP_H}{dt_A}$$

$$\frac{dP_H}{dt_H} = \frac{\frac{g'}{\phi_H} - \left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right) X'}{Z}$$

$$\frac{dP_{E100}}{dt_H} = \frac{dP_H}{dt_H} + 1$$

$$\frac{dP_A}{dt_H} = \frac{\phi_H}{\phi_A} \frac{dP_H}{dt_H}$$

$$\frac{dP_F}{dt_H} = \alpha \frac{\phi_H}{\phi_A} \frac{dP_H}{dt_H}$$

$$\frac{d\theta}{dt_H} = -\phi_H \left(\frac{1}{\phi_H} - \frac{\alpha}{\phi_A}\right) \frac{dP_H}{dt_H} - 1$$

$$\frac{dP_{SC}}{dt_H} = \phi_H \frac{dP_H}{dt_H}$$

$$\frac{dP_S}{dt_H} = \frac{\phi_H}{\phi_S} \left(1 - \frac{\delta_H}{\phi_H} - \frac{\delta_A}{\phi_A}\right) \frac{dP_H}{dt_H} \qquad \text{(A1.5)}$$

Appendix 2. Calibration of the Shift in the Demand for Fuel and Hydrous Ethanol

We use a logistic function of the form

$$X(\theta) = \frac{A}{1 + Be^{-C\theta}} + D \tag{A2.1}$$

where parameters *A*, *B*, and $C > 0$ and $D < 0$. As $\theta \to \infty$, $X \to A + D$; therefore, the value $A + D$ represents the upper asymptote of the function (A2.1). Similarly, $\theta \to -\infty$ implies $X \to D$, which defines the lower asymptote of the logistic function.

In calibrating the curve (A2.1), we set the upper asymptote equal to the quantity of the fuel blend consumed by flex cars in the baseline, because flex cars are capable of running on the fuel blend (a mixture of gasoline and anhydrous ethanol) while non-flex cars cannot use hydrous ethanol. If the relative price changes in favor of hydrous ethanol, the maximum outward shift in the demand for hydrous ethanol is equal to quantity of fuel consumed by flex cars in the baseline, denoted as U_0; therefore

$$A + D = U_0 \tag{A2.2}$$

The lower asymptote is equal to the quantity of hydrous ethanol in the baseline because this is the maximal shift in hydrous demand if the relative price changes in favor of fuel blend. This quantity is directly observable and is denoted as L_0

$$D = L_0 \tag{A2.3}$$

It follows directly from equations (A2.2) and (A2.3) that the parameter *A* equals

$$A = U_0 - L_0 \tag{A2.4}$$

We use the parameter *B* to change the curvature of the logistic function; thus it is assumed to be known, and we vary its value. Recognizing that the observed baseline represents a situation with no shift in the fuel and hydrous ethanol demand (the shifts have already occurred and thus are not observed), we must have $X\left(\theta_0\right)=0$, where θ_0 denotes the difference between fuel and hydrous ethanol price in the baseline. Then, invoking equation (A2.1), for the parameter C we obtain

$$C=-\frac{1}{\theta_0}\ln\left[-\frac{1}{B}\frac{U_0}{L_0}\right] \tag{A2.5}$$

Appendix 3. Documentation of Fuel Taxes in Brazil for Gasoline and Ethanol

There are two "fuels" consumed in Brazil: E100 (100 percent hydrous ethanol consumed by flex cars) and "fuel" (a mixture of anhydrous ethanol and petroleum-based gasoline). The price of E100 is given by

$$P_{E100} = P_H + t_H + m_{E100}$$

where P_{E100} denotes the consumer price of hydrous ethanol, P_H denotes the wholesale market price of hydrous ethanol, t_H denotes the E100 fuel tax, and m_{E100} denotes a constant marketing margin.

The price of fuel P_F is a weighted average of the anhydrous ethanol price P_A and gasoline price P_G

$$P_F = \alpha\left(P_A + t_A\right) + \left(1-\alpha\right)\left(P_G + t_G\right) + m_F$$

where α denotes the mandated volume of anhydrous ethanol in total fuel, and t_A and t_G denote taxes on anhydrous ethanol and gasoline, respectively.

In general, the value of α varies. In 2010/11 (the marketing year beginning April 1), there were three months when the blend mandate for anhydrous ethanol was 20 percent; it was 25 percent for the other months that marketing year. Until October of the 2011/12 marketing year, the mandate was 25 percent after which it has been 20 percent.

The taxes in Brazil vary by state. In this study, we use taxes in the state of São Paulo because most of the ethanol in Brazil is produced and consumed in São Paulo. It is important to realize that there are four taxes on gasoline and three on hydrous ethanol, some of which are ad valorem and others are specific. The anhydrous tax is an ad valorem tax.

The tax on gasoline has four components. First, there are two federal *per unit taxes*: the *CIDE* tax of R$0.23/liter and the *PIS/COFINS* tax of R$0.2626/liter. The CIDE value can vary between years and within years according to the perceived political need to adjust the final price paid by fuel consumers. In 2010/2011 the average CIDE is R$0.2186 and it is R$0.1708 in 20011/12 (from March 1 2011 to February 2012 as data for March 2012 is not yet available).

Because the wholesale gasoline price reported by the ANP — a government agency— includes the *CIDE* and *PIS/COFINS* taxes, we first need to calculate the gasoline price without these two specific taxes. The reported gasoline price with taxes was R$1.54/liter and R$1.53, for 2010/11 and 2011/12, respectively. This means that the implied wholesale market price of gasoline equals R$1.0451 and R$1.099 for each season (before any marketing margin to the retail gas pump is added).

Second, we calculate the *ad valorem* tax called the ICMS which is 25 percent of the gasoline price given by ANP at R$1.54 and R$1.53, for 2010/11 and 2011/12, respectively. Therefore, the ICMS for gasoline was R$0.512/liter and now it is R$0.5104/liter.

Third, we calculate the ICMS- ST tax, which is 56.35 percent of the ICMS tax calculated above. It is the total cost that is directly attributed to the ICMS. The value of this ICMS-ST is therefore R$0.289 for 2010/201 and R$0.288 for 2011/12. While there is no sales tax *per se* in Brazil, every manufacturer, distributor, retailer, and provider of almost every type of merchandise or service pays the state *ICMS* and passes the cost along to the consumer. It is largely a “hidden” tax, in that it is not reported on any consumer’s receipt or directly on the price of the goods.

Finally, we add all the gasoline taxes to obtain the total gasoline taxes of R$ 1.2827 and R$1.2305 for these two periods, respectively.

The tax applied on anhydrous ethanol t_A is only the PIS/COFINS of R$0.048/liter.

The tax on hydrous ethanol t_H has three components. First, we have *PIS/COFINS for the producers* R$0.0048/l and PIS/COFINS for distributers at R$0.072. The producer price is given by CEPEA (Center for Advanced Studies on Applied Economics) at R$0.982 in 2010/11 and R$1.207 in 2011/12.

The margin for the distributer is R$0.05 for both periods. We add the PIS/COFINS taxes and the margin to the producer price (it give us R$1.04 for 2010/11 and R$1.26 for 2011/12) and from there we calculate the second tax that is the *ICMS*.

To calculate the ICMS at 12 percent, we add the number we got above to the PIS/COFINS for the distributers (R$0.072) and multiply the sum by 12 percent. For 2010/11 the ICMS is R$0.151 and for 2011/12 it is R$ 0.182/liter.

Finally, we calculate the third tax, that is, the *ICMS ST*. It is 25 percent of the values we got from the ICMS described above. The values calculated are R$0.038 and R$0.045 for 2010/22 and 2011/12, respectively.

The total hydrous tax is R$0.26 for 2010/11 and R$0.30 for 2011/12 (from March to February). In summary, the total hydrous tax is the sum of the PIS/COFINS for the producer and distributer and the ICMS taxes.

Data Sources

CEPEA (Center for Advanced Studies on Applied Economics), ethanol market price, data available at
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ICMS-ST substituição tributária, available at
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Taxes on Goods and Services — ICMS — Impostos Sobre Circulação de Mercadorias e Prestação de Serviços (Merchandise and Services Circulation Tax) data available at
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Appendix 4. Data Used to Calibrate the Model

Variable/parameter	Symbol	2010/11	2011/12	Unit	Source
PARAMETERS					
Kilometers per liter of anhydrous ethanol relative to gasoline	λ_A	0.67	0.67		UNICA
Kilometers per liter of hydrous ethanol relative to gasoline	λ_H	0.67	0.67		UNICA
Kilometers per liter of fuel blend relative to gasoline	λ_F	0.92	0.92		$\lambda_F = \alpha_v\lambda_A + (1-\alpha_v)$
Tonnes of sugar per tonne of sugarcane	ϕ_S	0.133	0.130		CONAB
Liters of anhydrous ethanol per tonne of sugarcane	ϕ_A'	71.74	68.59	liter/tonne	CONAB
Liters of hydrous ethanol per tonne of sugarcane	ϕ_H'	75.03	71.56	liter/tonne	CONAB
GEELs of anhydrous ethanol per tonne of sugarcane	ϕ_A	48.07	45.96	GEEL/tonne	$\phi_A = \lambda_A\phi_A'$
GEELs of hydrous ethanol per tonne of sugarcane	ϕ_H	50.27	47.95	GEEL/tonne	$\phi_H = \lambda_H\phi_H'$
Liters of ethanol from molasses per tonne of sugarcane	δ'	9.25	9.25	liter/tonne	CONAB
GEELs of ethanol from molasses per tonne of sugarcane	δ	6.20	6.20	GEEL/tonne	$\delta = \lambda_A\delta'$
Liters of anhydrous ethanol from molasses per tonne of sugarcane	δ_A'	2.69	3.67	liter/tonne	$\delta_A' = \mu_A\delta'$
GEELs of anhydrous ethanol from molasses per tonne of sugarcane	δ_A	1.80	2.46	GEEL/tonne	$\delta_A = \lambda_A\delta_A'$
Liters of hydrous ethanol from molasses per tonne of sugarcane	δ_H'	6.56	5.58	liter/tonne	$\delta_H' = \mu_H\delta'$
GEELs of hydrous ethanol from molasses per tonne of sugarcane	δ_H	4.40	3.74	GEEL/tonne	$\delta_H = \lambda_H\delta_H'$
Share of anhydrous ethanol in total ethanol production	μ_A	0.29	0.40		$\mu_A = C_A'/(C_A' + D_H')$
Share of hydrous ethanol in total ethanol production	μ_H	0.71	0.60		$\mu_A = D_H'/(C_A' + D_H')$
Share of sugar production consumed domestically	$1 - \sigma$	0.33	0.33		$1 - \sigma$
Share of sugar production exported	σ	0.67	0.67		UNICA/CONAB
Net processing cost of sugar per tonne of sugarcane	$\phi_S\xi_S - \psi_S$	46.56	58.87	\$/tonne	$\phi_S\xi_S - \psi_S = \phi_S P_S + \delta_A P_A + \delta_H P_H - P_{SC}$
Net processing cost of anhydrous ethanol per tonne of sugarcane	$\phi_A\xi_A - \psi_A$	28.54	29.67	\$/tonne	$\phi_A\xi_A - \psi_A = \phi_A P_A - P_{SC}$
Net processing cost of hydrous ethanol per tonne of sugarcane	$\phi_H\xi_H - \psi_H$	16.01	17.33	\$/tonne	$\phi_H\xi_H - \psi_H = \phi_H P_H - P_{SC}$
POLICY VARIABLES					
Tax on gasoline (volumetric)	t_G	1.28	1.23	\$/liter	SINDICOM
Tax on anhydrous ethanol (volumetric)	t_A'	0.05	0.05	\$/liter	SINDICOM
Tax on anhydrous ethanol (energy)	t_A	0.07	0.07	\$/GEEL	$t_A = t_A'/\lambda_A$
Tax on hydrous ethanol (volumetric)	t_H'	0.26	0.30	\$/liter	SINDICOM
Tax on hydrous ethanol (energy)	t_H	0.39	0.45	\$/GEEL	$t_H = t_H'/\lambda_H$
Blend mandate (volumetric)	α_v	0.246	0.231		$\alpha_v = C_A'/D_F'$
Blend mandate (energy)	α_E	0.18	0.17		$\alpha_E = \lambda_A\alpha_v/(1 + \lambda_A\alpha_v - \alpha_v)$
ELASTICITIES					
Elasticity of sugarcane supply	η^S_{SC}	0.50			Schmitz et al. (2003)
Elasticity of domestic demand for sugar	η^D_{DS}	-0.75			de Freitas and Kaneko (2011)
Elasticity of export demand for sugar	η^D_{XS}	-2.00			Schmitz et al. (2003)
Elasticity of demand for fuel (E25)	η^D_F	-0.23			Menezes et al. (2008)
Elasticity of demand for hydrous ethanol (E100)	η^D_H	-0.68			Menezes et al. (2008)

Note: The data sources are documented below.

Appendix 4. Data Used to Calibrate the Model (continued)

Variable/parameter	Symbol	2010/11	2011/12	Unit	Source
PRICES					
Price of gasoline (volumetric)	P_G	1.05	1.10	$/liter	ANP
Fuel price (volumetric)	P_F'	2.47	2.66	$/liter	ANP
Fuel price (energy)	P_F	2.68	2.88	$/GEEL	$P_F = P_F'/\lambda_F$
Price of anhydrous ethanol (volumetric)	P_A'	1.18	1.42	$/liter	CEPEA
Price of anhydrous ethanol (energy)	P_A	1.76	2.12	$/GEEL	$P_A = P_A'/\lambda_A$
Price of hydrous ethanol (volumetric)	P_H'	0.96	1.19	$/liter	CEPEA
Price of hydrous ethanol (energy)	P_H	1.43	1.78	$/GEEL	$P_H = P_H'/\lambda_H$
Consumer price of hydrous ethanol (volumetric)	P_{E100}'	1.54	1.88	$/liter	ANP
Consumer price of hydrous ethanol (energy)	P_{E100}	2.29	2.80	$/GEEL	$P_{E100} = P_{E100}'/\lambda_H$
Price of sugarcane	P_{SC}	56.11	67.83	$/tonne	IEA
Price of sugar	P_S	700.93	884.00	$/tonne	ERS
Marketing margin for fuel (volumetric)	m_F'	0.41	0.53	$/liter	$m_F' = P_F' - \alpha_v(P_A' + t_A') - (1 - \alpha_v)(P_G + t_G)$
Marketing margin for fuel (energy)	m_F	0.44	0.57	$/GEEL	$m_F' = P_F - \alpha_E(P_A + t_A) - (1 - \alpha_E)(P_G + t_G)$
Marketing margin for E100 ethanol (volumetric)	m_{E100}'	0.31	0.39	$/liter	$m_{E100}' = P_{E100}' - P_H' - t_H'$
Marketing margin for E100 ethanol (energy)	m_{E100}	0.47	0.57	$/GEEL	$m_{E100} = P_{E100} - P_H - t_H$
Price gap between fuel and hydrous ethanol	θ	0.393	0.082	$/GEEL	$\theta = P_F - P_{E100}$
QUANTITIES					
Consumption of anhydrous ethanol (volumetric)	C_A'	7.51	8.49	billion liters	$C_A' = D_F' - C_G$
Consumption of anhydrous ethanol (energy)	C_A	5.03	5.69	billion GEELs	$C_A = \lambda_A C_A'$
Consumption of hydrous ethanol (volumetric)	D_H'	15.29	10.19	billion liters	UNICA
Consumption of hydrous ethanol (energy)	D_H	10.24	6.83	billion GEELs	$D_H = \lambda_H D_H'$
Consumption of gasoline (volumetric)	C_G	22.99	28.31	billion liters	UNICA
Consumption of fuel (volumetric)	D_F'	30.50	36.80	billion liters	UNICA
Consumption of fuel (energy)	D_F	28.02	34.00	billion GEELs	$D_F = \lambda_F D_F'$
Production of sugarcane	S_{SC}	0.62	0.57	billion tonnes	CONAB
Production of anhydrous ethanol (volumetric)	Q_A'	8.32	8.59	billion liters	UNICA
Production of anhydrous ethanol (energy)	Q_A	5.58	5.76	billion GEELs	$Q_A = \lambda_A Q_A'$
Production of hydrous ethanol (volumetric)	Q_H'	19.05	14.05	billion liters	UNICA
Production of hydrous ethanol (energy)	Q_H	12.77	9.42	billion GEELs	$Q_H = \lambda_H Q_H'$
Residual anhydrous ethanol (volumetric)	I_A'	0.40	1.22	billion liters	UNICA
Residual anhydrous ethanol (energy)	I_A	0.27	0.82	billion GEELs	$I_A = \lambda_A I_A'$
Residual hydrous ethanol (volumetric)	I_H'	0.68	1.62	billion liters	UNICA
Residual hydrous ethanol (energy)	I_H	0.46	1.09	billion GEELs	$I_H = \lambda_H I_H'$
Quantity of sugarcane devoted to sugar production	C^S_{SC}	0.29	0.28	billion tonnes	Derived from equation (8)
Domestic consumption of sugar	D^D_S	0.01	0.01	billion tonnes	$D^D_S = (1-\sigma)\phi_S C^S_{SC}$
Foreign consumption of sugar	D^W_S	0.03	0.02	billion tonnes	$D^W_S = \sigma\phi_S C^S_{SC}$

Note: The data sources are documented below.

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CHAPTER 3

Emissions from Land Use Change: Do they Really Matter Given Fuel Market Leakage?

1. Introduction

The issue of carbon leakage – which arises when the greenhouse gas (GHG) emissions reductions offered by an environmental policy are partially or more than offset by the market effects of the policy – is often raised as an obstacle to the success of environmental policies. Leakage has been extensively studied in the context of cap and trade policies (see Wooders et al. 2009 for a survey), reduced deforestation and land degradation (REDD) policies (e.g., Murray 2008), and the indirect land use change associated with biofuels policies (e.g., Searchinger et al. 2008).[59]

Although emissions from land use change due to biofuel policies have attracted a significant amount of research, leakage in the fuel market itself –which arises since the addition of biofuels always causes a reduction in the world gasoline market price—has been studied less.[60] Leakage in the fuel market is the focus on this paper. To our knowledge, de Gorter and Just (2009a) are probably the first to recognize this effect (calling it the "indirect output use effect"), but they only discuss its intuition and do not provide an analysis for individual biofuel policies. Chen et al. (2011) use a dynamic, spatial, multi-market equilibrium model to examine changes along the extensive and intensive margin of land use in the United States that are induced by biofuel policies and the implications of these policies for GHG emissions. Although they provide estimates of leakage in the fuel market, they model the biofuel mandate differently than we do. They assume that consumers can choose between ethanol and gasoline even when

[59] There are numerous studies on land use change. Al-Riffai et al. (2010) provide one of many surveys.
[60] In other words, we seek to quantify the changes in the fuel market resulting from the introduction of biofuels via various biofuel policies. Production of biofuels is the only shock to the fuel market we analyze; for example, we do not investigate how much world gasoline (oil) consumption would change with an oil supply shock.

the use of ethanol is mandated; hence, in their model the ethanol price (in energy equivalent) is equal to the price of gasoline. In our model, the price of fuel (which is a blend of ethanol and gasoline) is a weighted average of the ethanol and gasoline prices (in energy equivalent), where the weights are equal to ethanol and gasoline's respective shares of the fuel blend. Rajagopal et al. (2011) empirically estimate fuel market leakage related to the U.S. ethanol blend mandate and find that the U.S. blend mandate combined with a blenders' tax credit results in a reduction in global carbon emissions.[61] In contrast, we find that corn-ethanol policies are associated with an increase in carbon emissions.[62]

Although U.S. ethanol policies historically have been motivated primarily by concerns related to energy security, local air pollution, and farm income support, the U.S. introduced legislation in 2007 which specifically requires that ethanol reduce GHG emissions by 20 percent (relative to the gasoline it is assumed to replace). The 20 percent figure is estimated based on "life-cycle accounting" (LCA), which reflects a "well to wheel" measure of GHG emissions from gasoline production and a "field to fuel tank" measure of emissions from ethanol production (Farrell et al. 2006). If this requirement is not met, the ethanol is not eligible for tax credits or for being counted towards the mandate.

Given the recent concern in the U.S. about global climate change, the corn-ethanol lobby seized upon the benefits of ethanol in reducing GHG emissions. However, this strategy has back-fired because the LCA method is inherently flawed, as highlighted by Searchinger et al. (2008) who show that U.S. corn-ethanol emits greater GHG emissions relative to gasoline if changes in

[61] For brevity, when we use the term "carbon emissions" in the paper we mean carbon-equivalent greenhouse gas emissions which are generated at combustion.

[62] Du and Hayes (2009) find that U.S. ethanol production pushes the wholesale gasoline prices down, but this is not leakage as it is defined in the literature. They obtain their result because they assume the oil price is fixed and look only at the oil crack ratio and spread. They also do not take into consideration the market effects outside the United States. We endogenize the world oil price, which gives rise to the indirect output use change effect in the fuel market.

the use of land (e.g., converting forest into crop land) are correctly taken into consideration. The existence of leakage from land-use change sparked a controversy that reached a fever pitch and eventually led to both the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) revising their 20 percent estimate of ethanol's relative GHG benefit to reflect emissions from land use changes.[63]

Instead of focusing on indirect land use change, this paper addresses the issue of whether corn-ethanol still meets the 20 percent threshold when (direct) fuel market leakage is taken into account. We define "market leakage" as a market effect of biofuels in *displacing* gasoline and other oil (domestic non-transportation and international oil) consumption[64]. The LCA estimate of emissions savings from a gallon of ethanol assumes that ethanol replaces an (energy-equivalent) gallon of gasoline—i.e., LCA assumes there is no market leakage in the fuel market. However, leakage inevitably exists in the fuel market, as it exists in land and other markets related to biofuels production and consumption. In this paper, we advance an analytical framework to analyze the fuel market leakage of two biofuel policies—a blender's tax credit and a mandate—by themselves and in combination.

We find that for the same quantity of ethanol, fuel market leakage due to a tax credit is always greater than that due to a binding mandate. We also find that the combination of a binding mandate and a tax credit produces greater fuel market leakage than a mandate alone. Although the land market does not enter our analytical model explicitly, we do capture land use

[63] CARB made their ruling on land use change in April of 2009, while the EPA made their ruling in February 2010. The revised EPA ruling included not only an estimate of land use change due to ethanol, but also a revised and substantially lower LCA estimate. As a result, even with land use change, corn-ethanol still meets the threshold, provided relatively more 'clean' inputs like natural gas are used instead in the production of ethanol.

[64] Life-cycle accounting that underpins the binary sustainability thresholds, such as the U.S. requirement that corn-ethanol reduce GHG emissions by 20 percent relative to gasoline, assumes that one gallon of ethanol (gasoline equivalent) *replaces* one gallon of gasoline.

change effect through an emissions savings parameter derived from the EPA's RFS2 ruling in February 2010.

In addition to quantifying the fuel market leakage effects, our paper also contributes to the biofuels debate by providing a more complete analysis of the carbon emission effects of biofuels policies by taking into account fuel market leakage. For example, we show that while the addition of a tax credit to a binding ethanol consumption mandate has no effect on the ethanol market price, the ethanol price increases if the tax credit is combined with a blend mandate. In addition, a tax credit combined with a binding mandate always alleviates international leakage, though perhaps only marginally, because it causes an increase in the gasoline market price.

Our analysis finds that one gasoline-energy equivalent gallon of ethanol replaces only 0.19 to 0.37 gallons of gasoline and the rest (0.63 and 0.81 gallons, respectively) is displaced (i.e., contributes to higher fuel consumption). The significant fuel market leakage combined with the land use leakage makes one gallon of ethanol emit as much as 16 percent more carbon than one gallon of gasoline. This is a key finding: U.S. corn ethanol does not meet the EPA's 20 percent "sustainability standard".

The remainder of the paper is organized as follows. The next section defines market leakage, describes the emissions savings effect of corn ethanol with and without consideration of petroleum by-products, and derives a rule to determine whether or not corn ethanol meets the EPA's sustainability standard. In Section 2, we analyze market leakage due to a blenders' tax credit. For analytical tractability, we do not model crude oil (which is proxied by gasoline) or petroleum by-products, but our theoretical findings also hold for the more complex numerical model. In Section 3, we investigate market leakage under a binding consumption mandate, and we extend the analysis to a binding blend mandate in Section 4.[65] The data and procedures used to calibrate the numerical model are presented in Section 5. In Section 6, we present our results. The last section provides some concluding remarks.

2. Market Leakage (Indirect Output Use Change Effect) and Changes in Global Carbon Emissions due to Ethanol

At combustion, one gasoline-energy equivalent gallon (GEEG) of ethanol emits less carbon dioxide (CO_2) than one gallon of gasoline. Letting e_G and e_E denote kilograms of CO_2 emitted per GEEG of ethanol and gasoline, respectively, the term

$$\xi = \frac{e_G - e_E}{e_G} \tag{1}$$

represents carbon savings of ethanol relative to gasoline; for example, a value $\xi = 0.20$ means that one GEEG of ethanol emits 20 percent less carbon than the same quantity of gasoline. Embedded in expression (1) is the EPA's assumption that every GEEG of ethanol consumed replaces one gallon of gasoline.

However, gasoline is one of several products which are jointly produced from crude oil, so ethanol also replaces the by-products of gasoline production, such as distillate fuel oil or kerosene; it is generally assumed that the gasoline and by-product quantities are linked through a fixed production coefficient.[66] The existence of by-products is not reflected in the EPA's estimates of CO_2 savings of ethanol. Denoting β_G and β_B as GEEGs of gasoline and by-products

[65] We model both a consumption mandate and a blend mandate because in theory the U.S. mandate is a consumption mandate but it is implemented on a yearly basis as a blend mandate. Some authors model it as a consumption mandate (e.g., Lapan and Moschini 2012), while others model it as a blend mandate (e.g., de Gorter and Just 2009). Furthermore, the distinction facilities exposition as the consumption mandate is more straightforward and the extension to a blend mandate makes it easier to understand.

[66] We assume that oil is not a substitute for other primary energy sources, such as coal or natural gas. Therefore, leakage estimates presented in this paper are a lower bound if one allows for any substitutability between oil and other primary energy sources.

per barrel of crude oil, respectively, the ratio of the quantity of gasoline (G) and by-products (B) is given by

$$\frac{G}{B} = \frac{\beta_G}{\beta_B} \tag{2}$$

Equation (2) implies that associated with one GEEG of gasoline are β_B/β_G GEEGs of petroleum by-products. Therefore, the CO_2 savings of one GEEG of ethanol relative to one GEEG of gasoline and a corresponding quantity of the petroleum by-products are

$$\theta = \frac{e_G + \frac{\beta_B}{\beta_G} e_B - e_E}{e_G + \frac{\beta_B}{\beta_G} e_B} \tag{3}$$

where e_B denotes the CO_2 emissions of a GEEG of by-products.[67] The interpretation of equation (3) is analogous to that of equation (1). A comparison of equations (1) and (3) yields $\theta > \xi$. Intuitively, the carbon savings of ethanol are expected to be higher when petroleum by-products are included; in addition to reducing gasoline consumption, ethanol also reduces consumption of the by-products (which are produced in a fixed proportion to gasoline) and the carbon associated with the by-products' consumption.

Let E denote the volume of gasoline energy-equivalent gallons of ethanol which are introduced to the fuel market because of a biofuels policy. The additional ethanol volume will affect relative prices and hence also affect global consumption of gasoline and the petroleum by-products. An increase in ethanol consumption decreases the relative price of gasoline, which results in increased oil consumption in the rest of the world (ROW); hence, the EPA's implicit assumption that one GEEG of ethanol replaces gasoline one-to-one will not hold. To measure the

[67] In the numerical part of the paper, we show that $\theta = 0.79$ if land use change is not considered, and $\theta = 0.65$ when this effect is taken into account.

number of gallons of gasoline that are actually displaced (i.e., not replaced) by ethanol, we define market leakage as

$$L_M = \frac{\Delta G + E}{E} \tag{4}$$

where $\Delta G < 0$ denotes a reduction in global gasoline consumption due to the introduction of E GEEGs of ethanol. Although equation (4) defines market leakage solely in terms of gasoline and ethanol, the presence of petroleum by-products is implicitly embedded in the change in gasoline consumption, ΔG. For example, a value of $L_M = 0.7$ means that one GEEG of ethanol replaces only 0.3 gallons of gasoline and the rest, 0.7 gallons, is displaced.

If the initial consumption of ethanol is zero, and it increases to E GEEGs, the change in CO_2 emissions is given by[68]

$$\Delta \text{ in global } \mathrm{CO}_2 = e_E E + e_G \Delta G + e_B \Delta B \tag{5}$$

where ΔB denotes a change in global consumption of petroleum by-products.

Relationship (2) implies $\Delta B = (\beta_B / \beta_G)\Delta G$ and from equation (3), we have $e_E = (1-\theta)\left[e_G + (\beta_B/\beta_G)e_B\right]$. Substituting these expressions into equation (5) and rearranging, we obtain

$$\Delta \text{ in global } \mathrm{CO}_2 = \underbrace{-\theta\left[e_G + (\beta_B/\beta_G)e_B\right]E}_{\substack{\text{reduction in emissions associated with} \\ \text{consumption of ethanol}}} + \underbrace{\left[e_G + (\beta_B/\beta_G)e_B\right](E + \Delta G)}_{\substack{\text{change in emissions due to} \\ \text{market leakage}}} \tag{6}$$

[68] Throughout the paper, we assume that ethanol policies are implemented only in the Home country. While this assumption greatly simplifies the theoretical analysis, it makes no difference to our qualitative results because, in theory, one can always aggregate all countries producing biofuels into a Home country and treat the remaining countries as a Foreign country (as it is typically done in a partial equilibrium analysis). Because our numerical simulations are meant to illustrate and quantify our theoretical results, we follow the same principles and use the Unites States – the world's largest ethanol producer – as an example. Even though we do not model biofuel policies in every single country that produces biofuels, we note that leakage estimates are more sensitive to elasticities than they are to fuel consumption/production shares. This suggests that, for a given set of elasticities, our leakage estimates would not change significantly if more than two countries were analyzed.

The first term on the right-hand side of equation (5) represents a reduction in carbon emissions due to E GEEGs of ethanol relative to the same quantity of gasoline and corresponding by-products, assuming that ethanol replaces gasoline one-to-one. The second term represents a change in global carbon emissions – typically an increase – that occurs because of a change in the relative prices of ethanol, gasoline, and the petroleum by-products. To see this better, the term $E + \Delta G$ in equation (5) can be replaced by EL_M (from equation (4)). Therefore, total carbon emissions per GEEG of ethanol, taking into account the market leakage effect, are

$$\frac{(1-\theta)\left[e_G + (\beta_B/\beta_G)e_B\right]E + \left[e_G + (\beta_B/\beta_G)e_B\right]EL_M}{E} \tag{7}$$

where the first term in the numerator of expression (7) represents carbon emissions of corn ethanol, assuming it replaces gasoline one-to one. With expression (7), we are in a position to determine the overall carbon savings of one GEEG of corn ethanol relative to one GEEG of gasoline and associated petroleum by-products. To do that, we reuse definition (3) by substituting the overall carbon savings of ethanol, $(1-\theta+L_M)\left[e_G + (\beta_B/\beta_G)e_B\right]$ (obtained by simplifying expression (7)) for the term e_E in equation (3), to obtain[69]

$$\frac{e_G + (\beta_B/\beta_G)e_B - (1-\theta+L_M)\left[e_G + (\beta_B/\beta_G)e_B\right]}{e_G + (\beta_B/\beta_G)e_B} = \theta - L_M \tag{8}$$

Equation (8) shows that increasing corn ethanol consumption offers a net reduction in global carbon emissions if and only if $\theta - L_M > 0$ – i.e., if the emissions savings effect outweighs the indirect output use effect that is also known as leakage. For instance, if $\theta = 0.8$ and $L_M = 0.7$, the net savings of corn ethanol relative to gasoline and corresponding by-products are only 10 percent (and not 80 percent as assumed previously by policymakers).

[69] This result is in line with the finding of Stoft (2010).

Empirically, we will estimate the quantity on the right-hand side of equation (8) to determine whether corn ethanol meets a given EPA sustainability standard (for example, the current standard of 20 percent). This entails determining whether

$$\theta - L_M > \text{ EPA's sustainabilty standard} \qquad (9)$$

If condition (9) holds, corn ethanol meets the standard.

3. Market Leakage with a Blender's Tax Credit

Throughout the paper, we assume that gasoline and ethanol (in gasoline-equivalent terms) are perfect substitutes in consumption. Consumers do not distinguish between the two, so the only relevant market demand curve is one for fuel, which consumers demand in order to obtain miles traveled. A blender's tax credit is an ethanol consumption subsidy paid to fuel blenders for each gallon of ethanol blended with gasoline. Competition among blenders implies that the ethanol market price will be higher than the gasoline price by the amount of the tax credit.[70] In Appendix 1, we derive a formula for market leakage when ethanol production increases due to an increase in the blender's tax credit, using the definition of market leakage in equation (4):

$$L_M^{\tau} = \frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \phi\eta_{SH} - (1-\phi)\eta_{SF}} \qquad (10)$$

where τ denotes the blenders' tax credit, ρ denotes the Home country's share of world gasoline consumption, ϕ denotes the Home country's share of world gasoline production, and the η terms denote the relevant elasticities. The first subscript (*D* or *S*) in each elasticity term signifies an elasticity of fuel demand or supply, respectively, and the second subscript (*H* or *F*) denotes the country (Home or Foreign/Rest of world).

The value of market leakage in (10) is always non-negative and does not exceed unity,

[70] That the tax credit is modeled as a consumption subsidy follows from the increase in the ethanol market price.

which means that one GEEG of ethanol produced under the tax credit can replace at most one gallon of gasoline. The actual rate of replacement depends mostly on market elasticities and to a lesser extent on the consumption and production shares of the Home country. For illustration, assume that demand and supply elasticities are the same in both countries and are equal to -0.2 and 0.2, respectively. In this case, the market leakage due to a tax credit is 0.5 [x100] percent, meaning that one energy-equivalent gallon of ethanol replaces 0.5 gallons of gasoline. Notice that market leakage is independent of market shares if the demand and supply are equal in absolute values and do not vary between countries.

Since an ethanol production increase caused by a tax credit always lowers the world gasoline price, the tax credit increases not only international gasoline consumption but also domestic consumption (unless the Home country is “small” – i.e., its share of gasoline is small enough that it has no effect on the world gasoline price – see Appendix 1). Hence, we must distinguish between domestic leakage and international leakage.[71] Decomposing the total market leakage given by expression (10) into a domestic L_M^D and international L_M^I component, the relative share of domestic leakage depends on the consumption shares and demand elasticities in both countries. The relative domestic share of leakage does not depend on the fuel supply elasticities, since leakage occurs only along the demand curves; it is equal to

$$\frac{L_M^D}{L_M^I} = \left(\frac{\rho}{1-\rho}\right)\frac{\eta_{DH}}{\eta_{DF}} \tag{11}$$

Inspection of ratio (11) reveals that domestic leakage becomes more significant relative to international leakage as (*i*) the Home country’s share of world gasoline consumption increases, or (*ii*) the elasticity of demand for fuel in the Home country becomes more elastic relative to fuel

[71] We define domestic leakage as a change in fuel consumption – due to biofuels – occurring in the country that introduces biofuels, while international leakage denotes a change in fuel (gasoline) consumption in the rest of the world.

demand in the Foreign country. Therefore, if an ethanol-producing country[72] consumes a substantial share of world gasoline, the bias of market leakage estimates which ignore domestic leakage could be substantial. Likewise, if domestic demand for fuel is relatively elastic and only the international component of leakage is considered, estimates of market leakage are likely to underestimate its true value.

Is Market Leakage for a Small Country Always 100 Percent?

One might suppose that a biofuel policy of a small importer (exporter) in the gasoline market that faces a perfectly elastic excess supply (demand) curve of gasoline would necessarily have 100 percent leakage. The argument is that if a small country increases its production (and consumption) of ethanol, but this has no effect on gasoline prices (due to the small country assumption), then ethanol does not replace any gasoline. However, this does not necessarily have to be the case, and, under some conditions, a small country can have less leakage of its biofuel policies than a large country which influences the world gasoline price.

A small country in international markets faces a perfectly elastic excess supply/demand curve. The conditions under which it faces the perfectly elastic curve are derived in Appendix 2). We analyze the case of a perfectly elastic trade curve because of consumption and production shares.[73] Given this assumption, market leakage with a blenders' tax credit is equal to

$$\frac{\rho\eta_{DH}+(1-\rho)\eta_{DF}}{\rho\eta_{DH}+(1-\rho)\eta_{DF}-\rho\eta_{SH}-(1-\rho)\eta_{SF}}\leq 1 \tag{12}$$

If we assume further than the fuel demand and gasoline supply elasticities in both countries are -0.2 and 0.2, respectively, then market leakage is 50 percent – only half of what we might have expected for a small country.

[72] Or a coalition of countries.

[73] A small importer faces no market leakage provided that production technology in the Foreign country exhibits constant returns to scale which render the Foreign gasoline supply curve perfectly elastic. On the other hand, a small exporter sees 100 percent market leakage, if the fuel demand curve in the rest of the world is perfectly elastic.

4. Market Leakage with a Consumption Mandate

The economics of a biofuel consumption mandate are different from those of a blenders' tax credit. The tax credit is a taxpayer-financed ethanol consumption subsidy which raises the ethanol market price and hence increases ethanol supply from domestic production and imports. In contrast, the ethanol supply which is produced to meet a consumption mandate is financed by an implicit gasoline consumption tax which reduces the equilibrium quantity of gasoline and its market price. Gasoline producers are made worse off by a consumption mandate, but fuel consumers can be better off under some circumstances, since the mandate can either increase or decrease the fuel price (de Gorter and Just 2009b; Lapan and Moschini 2012).

Total market leakage from a consumption mandate depends on whether domestic fuel consumption decreases with the mandate. Total leakage may actually be negative (i.e., it would further reduce ethanol's GHG emissions relative to gasoline) if the reduction in domestic fuel consumption is larger than the increase in Foreign country gasoline consumption which occurs when the gasoline price decreases. We also note that even if the domestic fuel price increases with a mandate, global GHG emissions can increase; this result arises if one GEEG of ethanol replaces less than one gallon of gasoline and the emissions savings effect θ is sufficiently small. It can also be the case that the mandate decreases the domestic fuel price and decreases global GHG emissions as well; this result arises if the emissions savings effect θ is strong enough. Therefore, a reduction in the fuel price is not a sufficient condition for GHG emissions to increase.

The analytical formula for market leakage with a consumption mandate, denoted by L_M^{σ}, is equal to (see Appendix 3 for derivation)

$$L_M^{\sigma} = \frac{(\delta - 1)\eta_{DH}\left(\phi\eta_{SH} + (1-\phi)\eta_{SF}\right) - \rho\eta_{DH} - (1-\rho)\eta_{DF}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho\eta_{DH} - (1-\rho)\eta_{DF}} \tag{13}$$

where δ is the ratio of the intercept of the ethanol supply curve and the gasoline market price under the mandate. The structure of equation (13) is very similar to that of the market leakage formula for a tax credit in (10). The new parameter δ relates the ethanol mandate to the gasoline market. It is easy to show that $L_M^{\sigma} < 1$; expression (13) can also take on negative values, meaning that one gallon of ethanol can replace more than one gallon of gasoline.

Close inspection of equations (10) and (13) reveals that a binding consumption mandate is always superior to a blender's tax credit in terms of the magnitude of market leakage. This is stated by the following result.

Result 1: For the same quantity of ethanol, the market leakage due to a blenders' tax credit is always greater than that due to a consumption mandate. This follows immediately from the differencing of equations (10) and (13)

$$L_M^{\tau} - L_M^{\sigma} = \frac{(\delta - 1)\eta_{DH}\left(\phi\eta_{SH} + (1-\phi)\eta_{SF}\right)}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \phi\eta_{SH} - (1-\phi)\eta_{SF}} > 0$$

Intuitively, this result is driven by the way the two policies are financed. While a blenders' tax credit is a taxpayer-financed ethanol consumption subsidy, a consumption mandate is an implicit tax on gasoline (oil) producers (and sometimes also fuel consumers). This means that for the same quantity of ethanol, the gasoline (oil) price decreases more with a mandate than with the tax credit. This translates into lower global fuel consumption with a mandate, and hence less leakage under the mandate than under the tax credit.

Market Leakage when a Tax Credit is Added to a Binding Consumption Mandate

If a blender's tax credit is added to a binding consumption mandate for ethanol, the tax credit effectively subsidizes gasoline consumption, thus contradicting all environmental objectives (de Gorter and Just 2009b). In this case, the leakage due to the tax credit is infinite, because a tax credit does not induce additional ethanol production when a consumption mandate is binding. The tax credit's addition to a binding mandate does not cause any gasoline to be replaced by ethanol, but it *does* cause additional gasoline to be consumed (a displacement effect; see de Gorter and Just 2009b for reasoning). Because our definition of market leakage has the replaced gasoline quantity in the denominator, its value for the tax credit is infinite.

However, the market leakage due to the combination of the two policies is finite. The ethanol generated under a mandate does replace some gasoline, so the denominator of the fraction is not zero when the net effect of both policies is considered. However, total leakage of the combination of the two policies is greater than it would be with a mandate alone because of the oil consumption induced in the rest of the world by the tax credit.

In a special case, there could be a consumption mandate which is combined with a tax credit whose magnitude is such that by itself it would generate a quantity of ethanol equal to the consumption mandate. The following result shows what happens when these two policies are combined.

Result 2: If a binding consumption mandate is combined with a tax credit equal[74] to the price premium necessary to generate the mandated quantity of ethanol, then

[74] If the tax credit is less than the mandate premium (which almost has to be the case in reality when the mandate binds), then the market leakage in the large country case can still be positive, but may become negative if the mandate alone generates negative leakage; otherwise, leakage is greater with the policy combination than with the mandate alone.

i.) if the country is small in the world gasoline market, the tax credit exactly offsets the reduction in gasoline consumption due to the mandate and the market leakage of both policies combined is zero;

ii.) if the country is large in the world gasoline market, the tax credit more than offsets the reduction in gasoline consumption due to the mandate and the market leakage of both policies combined is positive.

Proof:

Denote P_F as the fuel price in the Home country with no policy. With no policy in place, we have $P_F = P_G$, where P_G denotes the world price of gasoline. Let P_F' be the fuel price in the Home country when both policies are introduced. The change in the domestic fuel price is equal to

$$\begin{aligned}\Delta P_F = P_F' - P_F &= \frac{\bar{E}}{C_F'}\left(\bar{P}_E - t_c^*\right) + \left(1 - \frac{\bar{E}}{C_F'}\right)P_G' - P_G = \left(\bar{P}_E - P_G' - t_c^*\right)\frac{\bar{E}}{C_F'} + P_G' - P_G \\ &= \left(\bar{P}_E - P_G - t_c^* - \Delta P_G\right)\frac{\bar{E}}{C_F'} + \Delta P_G\end{aligned} \tag{14}$$

where C_F' denotes fuel consumption with both policies, $\bar{P}_E$ denotes the ethanol price determined by the binding consumption mandate of $\bar{E}$ gallons of ethanol, P_G' denotes the world gasoline price with the policies, and $t_c^* = \bar{P}_E - P_G$ is the tax credit equal to the price premium necessary to generate the mandated quantity of ethanol with the tax credit alone.

Substituting the expression for the required tax credit back to equation (14) yields

$$\Delta P_F = \underbrace{\left(1 - \frac{\bar{E}}{C_F'}\right)}_{+}\underset{-}{\Delta P_G} \tag{15}$$

where the negative sign of ΔP_G in equation (15) follows from Appendix 3 and results in

$$sign\left(\Delta P_F\right) = sign\left(\Delta P_G\right)$$

Therefore, for a small country whose policies have no impact on world gasoline prices, it must be that $\Delta P_F = 0$. This means that domestic and foreign fuel consumption do not change with the implementation of the policies; hence, market leakage is zero. A consumption mandate combined with a tax credit in a large country reduces the world gasoline price and therefore the tax credit more than offsets the reduction in gasoline consumption due to the mandate and world fuel consumption increases, resulting in positive leakage.

5. Market Leakage with a Blend Mandate

We now analyze a biofuel blend mandate, which is a third policy option. Unlike the consumption mandate, under the blend mandate the quantity of ethanol to be consumed is not given in absolute terms, but rather given as a fixed share in the final fuel consumption in the economy. Although the economics of the two policies are not the same, it is easy to show that they produce identical outcomes if they yield the same quantity of ethanol production—i.e., if the blend mandate α is equal to the share of ethanol in the total domestic fuel consumption under the consumption mandate: $\alpha = \bar{E} / D_H\left(P_F\right)$. Substituting this blend requirement to the system (A4-1) in Appendix 4, it is clear that the equilibrium conditions for the consumption mandate (A3-1) in Appendix 1 are identical to those in (A4-1). Therefore, if the consumption and blend mandate generate the same quantity of ethanol, they also generate the same market leakage. Hence, Result 1 also applies to the blend mandate.

Market Leakage when a Tax Credit is Added to a Binding Blend Mandate

The addition of a tax credit to a preexisting binding blend mandate always increases the ethanol price, as shown by the last derivative in (A4-4) in Appendix 4. The ethanol price increases because the tax credit acts as a fuel consumption subsidy, reducing the fuel price (see the middle derivative in (A4-4)), increasing fuel consumption, and increasing ethanol production – a final outcome that is only achievable through a higher market price of ethanol. Unlike a blend mandate alone, a tax credit combined with a blend mandate always has an unambiguous impact on the ethanol and fuel prices. The effect of a higher tax credit combined with a binding blend mandate on the world gasoline price is also unequivocal – it increases, as shown by the first derivative in (A4-4). The gasoline price increases because of increased fuel consumption in the Home country; since the quantity of gasoline in the Home country is proportional to the quantity of fuel, $(1 - \alpha)$, blenders demand more gasoline which increases its market price.

It follows from the forgoing discussion that a tax credit in combination with a blend mandate alleviates (although possibly only marginally) the international leakage caused by a mandate alone, though at the same time it increases domestic leakage because it lowers the fuel price. The overall impact on leakage of adding a tax credit is thus indeterminate and depends mainly on supply and demand elasticities in both countries.

Unlike the effects explained for the consumption mandate in section 3 – where market leakage due to the addition of a tax credit resulted in infinite market leakage – the addition of a tax credit to a blend mandate results in finite (although positive) market leakage. Gasoline reduction is non-zero because the market price of ethanol increases, generating some ethanol production.

In the result to follow, we investigate what happens if a tax credit is added to a binding blend mandate when the tax credit's magnitude is such that by itself it would generate the same quantity of ethanol as the blend mandate alone. This tax credit differs from the tax credit whose ethanol quantity is equivalent to a consumption mandate; this accounts for the difference between Results 2 and 3.

Result 3: If a binding blend mandate is combined with a tax credit equal to the price premium necessary to generate the mandated quantity of ethanol with the tax credit alone, then

i.) if the country is small in the world gasoline market, the tax credit does not fully offset the reduction in gasoline consumption due to the mandate, and market leakage of both policies combined is negative—i.e., one energy-equivalent gallon of ethanol replaces more than one gallon of gasoline (but the negative leakage effect is not as strong as with the mandate alone);

ii.) if the country is large in the world gasoline market, the tax credit could more than offset, equally offset, or less than offset the reduction in gasoline consumption due to the mandate, depending on market parameters.

Proof:

Denote P_F as the fuel price in the Home country with no policy. In this case, $P_F = P_G$, where P_G denotes the world price of gasoline in the absence of either biofuel policy. Let P_F' be the fuel price in the Home country when both policies are combined. The change in fuel price is

$$\Delta P_F = P_F' - P_G = \alpha\left(P_E - \hat{t}_c\right) + \left(1-\alpha\right)P_G' - P_G \tag{16}$$

where P_E denotes the ethanol price under the two policies combined and $\hat{t}_c$ denotes the tax credit that would generate the same quantity of ethanol as the mandate alone. Let the ethanol price generated by the blend mandate α alone be $\hat{P}_E$. Then $\hat{t}_c = \hat{P}_E - P_G$, and equation (16) becomes

$$\Delta P_F = \alpha \Delta P_E + \left(1-\alpha\right)\Delta P_G \tag{17}$$

where $\Delta P_E = P_E - \hat{P}_E$ denotes a change in the price of ethanol from the situation with a blend mandate only to a situation where the mandate is combined with the tax credit; $\Delta P_G = P_G' - P_G$ denotes a change in gasoline price from the situation with no policy to a situation where both policies are combined. Therefore, the changes in ethanol and gasoline prices are not related to the same initial equilibrium.

As shown in Appendix 4, the addition of a tax credit to a pre-existing blend mandate increases the ethanol market price; therefore for a small country ($\Delta P_G = 0$), $\Delta P_F > 0$ and so, unlike with the consumption mandate, a combination of the blend mandate and the tax credit does result in a reduction in the Home country's fuel consumption. However, the direction of fuel consumption change is ambiguous for a large country because the gasoline price unambiguously decreases when a tax credit is added (Appendix 4), making the sign of ΔP_F indeterminate; the change in fuel consumption depends on market elasticities and consumption and production shares.

6. A Numerical Example

In this section, we empirically estimate the magnitude of market leakage of U.S. corn ethanol policies in 2009; we also determine whether U.S. corn ethanol meets the EPA's 20 percent sustainability standard. We use the numerical model detailed in Cui et al. (2011), but we calibrate it to a different set of biofuel policies: a binding mandate combined with a blenders' tax credit, ethanol production subsidy, and a feedstock (corn) production subsidy. Although the numerical model allows for a more detailed analysis compared to our theoretical framework – in that it considers oil, petroleum by-products, and the corn market – the theoretical insights and formulas for market leakage analyzed in the previous sections still hold. All the baseline data and their primary sources or formulas (if applicable) are presented in Appendix 5. All relevant data are converted into gasoline-energy equivalents to consistently model the linkages in the fuel market.

Data and Calibration

Biofuel policies have historically caused ethanol production in the United States (Drabik 2011). Although the ethanol mandate and blender's tax credit have perhaps been most influential in determining the quantity of ethanol consumed in the United States, the ethanol industry has also benefited from ethanol and corn production subsidies. U.S. ethanol consumption in 2009 amounted to 11.04 bil. gallons, which represents a 6 percent share (by energy) in total U.S. fuel consumption. The ethanol blenders' tax credit of $0.498/gallon consists of a federal component, equal to $0.45/gallon, and a state-level component, which is averaged at $0.048/gallon in 2009 (Koplow 2009). The ethanol production subsidy calculated by Koplow (2009) is $0.14/gallon in 2008. We assume the same level of the subsidy in 2009.

Corn subsidies in the U.S. totaled $3.79 bil. in 2009 (Environmental Working Group).[75] Of this total, $2.00 bil. consisted of decoupled subsidies. Following Sumner (2006), we assume a coefficient of 0.25 to represent the degree to which decoupled subsidies are actually coupled. The total production subsidy for corn is computed as follows: 0.25x $2.00 bil. + ($3.79 bil. - $2.00 bil.) = $2.29 bil. This translates to a subsidy of $0.17/bushel.

The U.S. fuel tax for gasoline was $0.49/gallon in 2009 (American Petroleum Institute). This includes the federal and state excise taxes as well as other taxes. We assume that the average tax on the petroleum by-products we consider is equal to 33 percent of the gasoline tax.

Following the analysis in de Gorter and Just (2010), we calibrate the model to a binding mandate (and other policies as described above). With the binding mandate, the price of fuel (a mix of ethanol and gasoline) is equal to the weighted average of ethanol and gasoline prices adjusted for the fuel tax and the tax credit. Corn and ethanol prices are linked through a zero profit condition for ethanol production; the prices of oil, gasoline, and petroleum by-products are similarly linked.

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[75] http://farm.ewg.org/progdetail.php?fips=00000&progcode=corn

In the feedstock (corn) market, we explicitly model the market effects of the co-product of ethanol production (Dried Distillers Grains with Solubles, DDGS)[76]. Following Hoffman and Baker (2011), we that assume 81 percent of DDGS is consumed domestically and the rest is exported.

Our numerical model uses demand and supply curves that exhibit constant price elasticities; this enables us to capture potentially non-linear effects from the introduction of ethanol in the analyzed markets. The elasticities' values are adopted from other studies (Gardner 2007; Hamilton 2009; and Cui et. al. 2011) and are presented in Appendix 5. Owing to the lack of econometric estimates, we assume, following Cui et al. (2011), that the demand for petroleum by-products has the same elasticity as the demand for fuel. We assume that the supply elasticity of oil in the ROW is 0.15; this assumption results in a reasonable estimate of demand elasticity for oil in the ROW, -0.29,[77] given our assumption that the elasticity of oil import supply facing the United States is 3.00 – the value used in Cui et al. (2011).

Carbon Emissions

An oil refinery produces various petroleum products, of which gasoline represents 46.1 percent by volume (Table 1). The implied volume of gasoline obtained from one barrel of oil (which is 42 gallons) is thus 0.461 x 42 = 19.362 gallons. The second column in Table 1 presents the implied volumes for the petroleum by-products as well. The total number of gallons (44.772) of all petroleum products obtained from one barrel of crude oil exceeds 42. This is known as the oil processing gain (equal to 6.6 percent in 2009), and it occurs because the density of oil products changes relative to the density of oil during the refining process. The third column in Table 1

[76] See Drabik (2011) for details on these effects.
[77] This demand elasticity is consistent with the results of a recent meta-analysis by Havránek et al. (2012).

provides shares of individual petroleum by-products (other than gasoline) of the total volume of by-products (25.41 gallons).

The actual yield of gasoline per barrel of crude oil differs from the theoretical one reported in the second column of Table 1. There are two reasons for the difference. First, the volume of 19.362 gallons does not take into account the 6.6 percent oil processing gain mentioned above. It is not clear, however, how to properly model the distribution of processing gain among the various oil products. Second, before fuel is sold at pump stations, special additives (other than ethanol) are mixed with the fuel to enhance its properties. These additives are produced from petroleum by-products. Hence, some volume of the by-products is actually used as fuel, and the effective volume of consumer "gasoline" per barrel of oil actually exceeds 19.362 gallons.

We calculate the actual number of gallons of gasoline per barrel of oil as follows. The total fuel consumption in the Unites States in 2009 amounted to 134.74 bil. gallons (physical volume). This includes gasoline, additives, and ethanol.[78] Ethanol consumption was 11.04 bil. gallons in 2009, and imports of additives (not produced from the oil processed in the United States) were 10.73 bil. gallons. Thus, the quantity of non-ethanol fuel (inclusive of additives) produced domestically is equal to 134.74 - 11.04 - 10.73 = 112.98 bil. gallons. Finally, we estimate the yield of gasoline per barrel of crude oil, equal to 21.483 gallons, by dividing the quantity of non-ethanol fuel produced in the U.S. (112.98 bil. gallons) by the quantity of oil processed in the U.S. in 2009 (5.26 bil gallons).

[78] We endogenize imports of additives by fixing the ratio of imports of additives to domestic gasoline production at its baseline value.

Table 1. Oil Products and Their Carbon Emissions

	Refinery yield (share)[a]	Gallons/barrel	Share in by-products	Adjusted gallons/barrel	kg CO_2/gallon [b]	Total kg CO_2/barrel
Gasoline	0.461	19.362		21.483	8.91	191.42
Distillate fuel oil	0.269	11.298	0.445	10.355	10.15	105.10
Kereosene type jet fuel	0.093	3.906	0.154	3.580	9.57	34.26
Residual fuel oil	0.040	1.680	0.066	1.540	11.79	18.15
Kerosene	0.001	0.042	0.002	0.038	9.76	0.38
Liquid refinery gases	0.041	1.722	0.068	1.578	6.00	9.47
Still gas	0.044	1.848	0.073	1.694	9.17	15.53
Petroleum coke	0.053	2.226	0.088	2.040	14.65	29.89
Finished aviation gasoline	0.001	0.042	0.002	0.038	8.32	0.32
Naptha for petrochemical feedstock use	0.013	0.546	0.021			
Other oils for petrochemical feedstock use	0.008	0.336	0.013			
Special naphthas	0.002	0.084	0.003			
Lubricants	0.010	0.420	0.017			
Waxes	0.001	0.042	0.002			
Asphalt and road oil	0.024	1.008	0.040			
Miscellaneous products	0.005	0.210	0.008			
Total	1.066	44.772				404.52
Subtotal for by-products (excluding gasoline)		25.410		23.289		

Notes:

[a] http://www.eia.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_a.htm

[b] http://205.254.135.7/oiaf/1605/coefficients.html

Without an established method to apportion the oil processing gain to individual petroleum products, and without adequate information about how much of each petroleum by-product is used to produce gasoline additives, we adjust the volumes of petroleum by-products per barrel of oil as follows. The total volume of the by-products is 23.289 gallons (=44.772 - 21.483). Then, we multiply this absolute total volume by the by-products' relative shares which are reported in the third column in Table 1. For example, the adjusted volume of distillate fuel oil is equal to 0.445 x 23.289 = 10.355 gallons, since distillate fuel oil comprises 44.5% of the petroleum by-products, by volume. We calculate the adjusted volumes only for petroleum by-products that get combusted (we assume that the consumption of non-combustible by-products such as Waxes does not contribute to CO_2 emissions).

The fifth column in Table 1 shows how much CO_2 is released when one gallon of the petroleum product is combusted. The last column gives the total CO_2 emissions which each product contributes to a barrel of oil. For example, gasoline contributes 191.42 kg/barrel = 21.483 gal of gasoline per barrel of oil x 8.91 kg/CO_2 per gallon of gasoline. The sum of the values across by-products, shown in the last column, equals the total CO_2 emissions associated with consuming a barrel of oil: 404.52 kg.

However, 404.52 kg CO_2 per barrel of oil is an underestimate because it ignores other emissions that occur before consumption (i.e., before combustion) such as emissions related to drilling of oil. We thus need to determine the CO_2 emissions of crude oil corresponding to its life-cycle analysis (LCA). To do that, we use the values given in Table 2. The total LCA (i.e., well-to-wheels) carbon emissions of gasoline are estimated to be 10.803kg/gallon; this translates into 21.483 x 10.803 = 232.07 kg/barrel. Approximately 80 percent of all carbon emissions of gasoline are released at combustion (i.e., tank-to-wheels). We assume that this ratio applies also to other petroleum by-products. Thus, we calculate the LCA emissions of petroleum by-products as 213.10/0.8 = 264.89kg/barrel, where the value of 213.10 represents the total emissions (at combustion) of petroleum by-products per barrel of oil. (It is the sum of the values in the last column in Table 1 exclusive of gasoline). We calculate carbon emissions of petroleum by-products by dividing carbon emissions of the by-products per barrel of oil (264.89 kg) by the sum of adjusted gallons/barrel of petroleum by-products from the fourth column in Table 1 (20.864 gallons); hence, we calculate the carbon emissions of the by-products to be 12.696 kg/gallon. Finally, the total carbon emissions per barrel of oil are given by the sum of gasoline and by-products emissions, that is, 232.07 + 264.89 = 496.96 kg/barrel.

In the numerical simulations, we assume two different scenarios for the carbon savings of corn ethanol relative to gasoline. In the first scenario, corn ethanol emits 52 percent less carbon emissions relative to gasoline, assuming a 100 percent replacement and no indirect emissions due to land use change. When emissions from land use change are included in this model, the relative savings of corn ethanol decreases to 21 percent (EPA, 2010). It is important to note, however, that these savings relate only to gasoline and ignore other potential savings due to petroleum by-products. Thus, to obtain estimates of the total carbon savings of ethanol relative to gasoline and corresponding petroleum by-products, we use equation (3) and values reported in Table 2 to arrive at carbon savings of 79 and 65 percent for the cases where emissions from land use change are excluded and included, respectively. Intuitively, the carbon savings should be higher when by-products are taken into account, because one gasoline-energy equivalent gallon of ethanol not only replaces gasoline, but also a corresponding quantity of petroleum by-products.

Table 2. Emission Intensities of Gasoline, Petroleum By-products, and Corn Ethanol

Variable	Symbol	Value	Unit	Source
Gasoline well-to-tank CO_2e emissions	G_{WT}	19,200	grams/mmBTU	EPA [a, b]
Gasoline well-to-wheels CO_2e emissions	G_{WW}	98,205	grams/mmBTU	EPA [c]
Gasoline tank-to-wheels CO_2e emissions	G_{TW}	79,005	grams/mmBTU	$G_{TW} = G_{WW} - G_{WT}$
mmBTUs per gallon of gasoline	σ	0.11	mmBTU/gallon	National Renewable Energy Laboratories (2008)
Gasoline well-to-tank CO_2e emissions (in kg/gallon)	G'_{WT}	2.11	kg CO_2e/gallon	$G'_{WT} = G_{WT}*\sigma/1000$
Gasoline well-to-wheels CO_2e emissions (in kg/gallon)	G'_{WW}	10.803	kg CO_2e/gallon	$G'_{WW} = G_{WW}*\sigma/1000$
Gasoline tank-to-wheels CO_2e emissions (in kg/gallon)	G'_{TW}	8.69	kg CO_2e/gallon	$G'_{TW} = G_{TW}*\sigma/1000$
Tank-to-wheels/well-to-wheels (=combustion/total emissions) ratio	κ	0.80		$\kappa = G'_{TW}/G'_{WW}$
CO_2 emissions of gasoline per barrel of oil, including LCA	μ_1	232.07	kg/barrel	$\mu_1 = \beta_G*G'_{WW}$
CO_2 emissions of petroleum by-products at combustion	μ_2	213.10	kg/barrel	Sum of the values in the last column in Table 1 exclusive of gasoline
CO_2 emissions of petroleum by-products (per barrel), including LCA	μ_3	264.89	kg/barrel	$\mu_3 = \mu_2/\kappa$
CO_2 emissions of petroleum by-products (per gallon), including LCA	μ_4	12.696	kg/gallon	$\mu_4 = \mu_3$/sum of adjusted gallons/barrel of petroleum by-products from Table 1
Total CO_2 emissions per barrel of oil	μ_T	496.96	kg/barrel	$\mu_T = \mu_1 + \mu_3$
Carbon savings of corn ethanol relative to gasoline				
Excluding land use change	ξ_{52}	0.52		RFA [d]
Including land use change	ξ_{21}	0.21		EPA [c]
Carbon savings of corn ethanol relative to gasoline & by-products				
Excluding land use change	θ_{52}	0.79		$\theta_{52} = (G'_{WW} + (\beta_B/\beta_G)*\mu_4 - z_{52})/(G'_{WW} + (\beta_B/\beta_G)*\mu_4)$
Including land use change	θ_{21}	0.65		$\theta_{21} = (G'_{WW} + (\beta_B/\beta_G)*\mu_4 - z_{21})/(G'_{WW} + (\beta_B/\beta_G)*\mu_4)$
Corn ethanol carbon emissions if 52% reduction relative to gasoline	z_{52}	5.19	kg CO_2e/GEEG	$z_{52} = (1-\xi_{52})G'_{WW}$
Corn ethanol carbon emissions if 21% reduction relative to gasoline	z_{21}	8.53	kg CO_2e/GEEG	$z_{21} = (1-\xi_{21})G'_{WW}$

Notes:

[a] nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1006DXP.txt (Table 2.5-8)

[b] mmBTUs = million British Thermal Units

[c] http://www.epa.gov/otaq/renewablefuels/420r10006.pdf (page 467 and Figure 2.6-1)

[d] http://renewablefuelsassociation.cmail1.com/T/ViewEmail/y/78B3C6C380747C63

7. Results

In this section, we empirically illustrate our theoretical findings. We analyze the market effects of three biofuel policies: an ethanol blender's tax credit, a consumption mandate, and a combination of the two. To be able to compare the effects of individual policies, we hold ethanol consumption constant and equal to its baseline level (11.04 bil. gallons = 7.63 bil. GEEGs). In all simulations, we set ethanol and corn production subsidies to zero. For ease of comparison, we express all prices and quantities in energy-equivalent terms.

The first column in Table 3 presents a market outcome under no biofuel policy (i.e., ethanol use is not mandated, and no blenders' tax credit is provided). In this situation, the free market price of ethanol ($1.82/GEEG) is too low to generate any ethanol production.[79] We take the no-policy values reported in the first column as benchmark values for evaluating the magnitude of market leakage associated with ethanol policies.

In the second column, we present the market effects of a blender's tax credit alone. To achieve the pre-determined level of ethanol consumption, a $0.87/gallon tax credit is required.[80] Notice that this tax credit is almost twice as high as the one actually used in 2009. The competition among fuel blenders for the tax credit bids the ethanol price up by $0.99/GEEG relative to the no-policy scenario. Ethanol consumption replaces some gasoline, thus reducing the world demand for oil. As a result, the oil market price decreases on net by $0.95/barrel, and the gasoline price decreases by $0.27/gallon. However, the reduction in the oil price is mitigated by an increase in the market price of petroleum by-products (it increases by $0.21/GEEG).

[79] This occurs because the intersection of the corn supply and demand curves (which corresponds to the intercept of the ethanol supply curve) is above the free market price of ethanol (Drabik, 2011).
[80] This corresponds to $1.27/GEEG of ethanol.

Table 3. Market Effects of A Biofuel Tax Credit and Mandate Relative to No Ethanol Production

	No policy	Tax credit	Mandate	Mandate & tax credit
		Difference relative to no policy		
Oil price ($/barrel)	61.98	-0.95	-1.08	-1.01
Gasoline price ($/GEEG)	2.04	-0.27	-0.31	-0.29
Ethanol price ($/GEEG)	1.82	0.99	0.99	0.99
Fuel price ($/GEEG)	2.53	-0.27	-0.24	-0.26
U.S. market price of petroleum by-products ($/GEEG)	1.54	0.21	0.24	0.22
U.S. consumer price of petroleum by-products ($/GEEG)	1.71	0.21	0.24	0.22
U.S. gasoline consumption (billion GEEGs)	116.57	-3.47	-3.95	-3.68
U.S. fuel additives (billion GEEGS)	11.07	-0.33	-0.38	-0.35
U.S. ethanol consumption (billion GEEGs)	0.00	7.63	7.63	7.63
U.S. fuel consumption (billion GEEGs)	127.65	3.83	3.30	3.60
U.S. consumption of petroleum by-products (billion GEEGs)	126.37	-3.76	-4.29	-3.99
ROW oil consumption (billion barrels) *	21.03	0.09	0.11	0.10
ROW gasoline consumption (billion GEEGs)	451.70	2.04	2.33	2.16
ROW by-product consumption (billion GEEGs)	489.66	2.21	2.53	2.35
World oil consumption (billion barrels)	26.45	-0.07	-0.08	-0.07

* ROW - rest of the world
Source: calculated

The price of petroleum by-products decreases because the reduction in global oil production results in a decrease in their production (since they are produced from crude oil through a fixed-coefficient technology) while demand for them remains unchanged.

As predicted by theory, the reduction in the oil price under the mandate alone in the third column ($-1.08/barrel) is greater than the reduction under the combination of policies in the fourth column ($-1.01/barrel).[81] The ethanol price increase is the same across all three policies, however, as they all share the same level of ethanol consumption. Although global oil consumption decreases due to the introduction of ethanol under each policy (between 0.07 to 0.08 bil. barrels), a lower oil price induces higher oil consumption in the ROW (between 0.09 to 0.11 bil. barrels).

Given that global oil consumption decreases under each policy, a question arises whether ethanol (in energy equivalent) replaces gasoline one-to-one as assumed by the EPA in constructing the sustainability standard for ethanol. The answer is no, and Table 4 shows how much gasoline is displaced (as opposed to replaced) by ethanol; the displaced gasoline volume represents market leakage, which is calculated using the formulas developed earlier.

The first row in Table 4, entitled *Most plausible parameters*, repeats the policy simulations presented in Table 3. For example, the value 0.812 under the tax credit policy means that the introduction of 1 GEEG of corn ethanol in the United States results in a global increase in fuel consumption by 0.812 GEEGs (see also equation (4).[82] Notice that if ethanol replaced gasoline one-to-one, then the change in global fuel consumption should be zero. Under the tax

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[81] When the tax credit is combined with the mandate, the tax credit is equal to $0.498/gallon.

[82] More specifically, the change in global fuel consumption is given by the sum of ethanol consumption and the change in global gasoline consumption. The former amounted to 7.63 bil. GEEGs (Table 3) and the latter is equal to 21.483 x (-0.07) = -1.43 bil. GEEGs, where 21.483 denotes GEEGs of gasoline per barrel of oil, and -0.07 denotes the reduction in global oil consumption from Table 3. Thus, the change in global fuel consumption is equal to 7.63 + (-1.43) = 6.20 bil. GEEGs (the rest of the world consumes only gasoline). One GEEG of ethanol is then associated with an increase in fuel consumption of 6.20/7.63 = 0.812 GEEGs.

credit, one GEEG of ethanol replaces only 1-0.812 = 0.188 gallons of gasoline. Consistent with the policy ordering predicted by the theory, the consumption mandate performs best in terms of market leakage (0.787), and the combination of the mandate and the tax credit has the second-least leakage.

The remaining rows in Table 4 show how sensitive the market leakage due to a biofuel policy is to the assumed elasticities of supply and demand curves in the world fuel market. The changes in elasticities in the second, third, and forth row are self-explanatory. In the scenario entitled *Inelastic fuel demand*, we assume that the elasticity of U.S. demand for fuel is -0.09; this value corresponds to the average short run elasticity reported by Havránek et al. (2012). In the last scenario, *Reversed yields of gasoline and petroleum by-products*, we assume, similarly to Cui et al. (2011), that there are no imports of gasoline additives in the calibration data. This implies that there are 23.52 and 21.25 gallons of gasoline and petroleum by-products, respectively, per barrel of crude oil.

All scenarios exhibit very stable and high levels of market leakage for all biofuel policies. The smallest market leakage arises in the case of very elastic U.S. oil supply relative to oil demand in the ROW, yet market leakage is quite high— above 60 percent— in this case. In summary, one GEEG of ethanol is empirically found to replace between 0.185 to 0.371 gallons of gasoline.

Even if world crude oil consumption decreases in response to consumption of ethanol, this does not necessarily mean that global carbon emissions decrease as well. Intuitively, this is possible because ethanol is not a carbon-free replacement of gasoline. Recall that the EPA only requires that corn-ethanol emits at least 20 percent less carbon relative to gasoline.

Table 4. Market Leakage

	Tax credit	Mandate	Mandate & tax credit
Most plausible parameters	0.812	0.787	0.801
Demand for petroleum by-products twice as elastic as demand for fuel	0.763	0.731	0.749
ROW oil demand twice as elastic as oil supply	0.815	0.790	0.804
ROW oil supply twice as elastic as oil demand	0.674	0.629	0.654
Inelastic fuel demand	0.782	0.773	0.778
Reversed betas	0.777	0.747	0.764

Source: calculated

We estimate the actual carbon savings of ethanol relative to gasoline and corresponding petroleum by-products in Table 5; all values are calculated as the difference between the emissions savings effect of ethanol relative to gasoline and the market leakage effect reported in Table 4 (see equation (8)). The actual carbon savings of corn ethanol are calculated under two situations, as mentioned above. In the first situation, we exclude emissions from land use change from total carbon emissions of ethanol, while in the second situation we include emissions from land use change. Because the latest EPA's ruling does include land use change emissions, the latter set of results is likely to be more relevant from a policy point of view.

To illustrate our results, consider first the actual carbon savings of ethanol under the *Most plausible parameters* case and tax credit, excluding emissions from land use change. The corresponding value of -2.3 percent is obtained as the difference between 0.789 [x100%] and 0.812 [x100%], where the former value is the carbon emissions savings effect of corn ethanol relative to gasoline and corresponding petroleum by-products (when emissions from land use change are excluded), and the latter value is the market leakage effect from Table 4. The interpretation of the carbon savings of -2.3% is straightforward: corn ethanol increases carbon emissions relative to gasoline and petroleum by-products by 2.3 percent. Two effects cause this result. First, we have shown that corn ethanol fails to replace gasoline one-to-one. Instead, the rate of replacement is much lower (19 – 37 percent), meaning that the carbon reducing effects of ethanol are difficult to produce when price adjustments are taken into account. Second, combustion of ethanol does not produce 100 percent less carbon emissions than gasoline combustion and petroleum by-products. In other words; the biofuel policy replaces a dirty fuel with a less dirty (but still not "clean") fuel.

Table 5. Actual Carbon Savings of Corn Ethanol Relative to Gasoline and Corresponding By-products (%) *

	Tax credit	Mandate	Mandate & tax credit
Excluding Land Use Change			
Most plausible parameters	-2.3	0.2	-1.2
Demand for petroleum by-products twice as elastic as demand for fuel	2.6	5.8	4.0
ROW oil demand twice as elastic as oil supply	-2.6	-0.1	-1.5
ROW oil supply twice as elastic as oil demand	11.5	16.0	13.5
Inelastic fuel demand	0.7	1.6	1.1
Reversed betas	1.2	4.2	2.5
Including Land Use Change			
Most plausible parameters	-16.0	-13.5	-14.9
Demand for petroleum by-products twice as elastic as demand for fuel	-11.0	-7.8	-9.6
ROW oil demand twice as elastic as oil supply	-16.2	-13.8	-15.2
ROW oil supply twice as elastic as oil demand	-2.1	2.4	-0.2
Inelastic fuel demand	-12.9	-12.0	-12.5
Reversed betas	-12.4	-9.4	-11.1

* A negative number means that corn ethanol emits more carbon than gasoline.

Source: calculated

Notice, however, that global carbon emissions decrease when ethanol is produced due to a mandate (first row and second column in Table 5). The reduction is only marginal, however, because one GEEG of ethanol reduces only 0.2 percent of carbon emissions relative to gasoline. A more significant reduction in relative emissions (16 percent) is achieved under the mandate with a very elastic oil supply curve in the ROW (fourth scenario). Nonetheless, corn ethanol does not meet the EPA sustainability standard of 20 percent. Because in this scenario we do not even consider the land use change effect and corn ethanol still fails the standard, it trivializes the controversy over how to measure land use change.

When emissions from land use change are taken into account, the carbon saving potential of corn-ethanol relative to gasoline declines significantly. For example, under the *Most plausible parameters* scenario, corn ethanol emits 13.5 – 16 percent more carbon than gasoline and corresponding petroleum by-products. In conclusion, our results suggest that it is very unlikely that U.S. corn ethanol meets the 20 percent sustainability standard imposed by the EPA.

8. Conclusions

Leakage is a measure of the ineffectiveness of an environmental policy and is frequently discussed in the context of combating global climate change. We develop an analytical framework to analyze not only leakage in the fuel market due to alternative biofuel policies, namely consumption subsidies and mandates (and their combination), but also to determine whether a biofuel meets a pre-determined sustainability standard.

Whether or not consumption of biofuels results in an increase in global greenhouse gas emissions depends on two factors. First, the market leakage effect determines the actual rate at which a biofuel replaces the fossil fuel. (We have focused here on corn ethanol and gasoline, respectively). Second, the emissions savings effect of a biofuel determines how much cleaner the biofuel is relative to the fossil fuel it is assumed to replace. In theory, global GHG emissions can decrease due to biofuel policies even if the biofuel does not replace the fossil fuel one-to-one, provided that the biofuel has significantly lower GHG emissions than the fossil fuel.

The international trade framework within which we analyze the biofuel policies gives rise to a distinction between domestic and international leakage. Under plausible assumptions, domestic leakage, which occurs in the country introducing the biofuels, can be a significant factor of total leakage (i.e., domestic and international combined). Because the world gasoline price (or equivalently, the crude oil price) declines with all analyzed biofuel policies, international leakage is always positive (meaning that one energy-equivalent gallon of ethanol replaces less than one gallon of gasoline), and domestic leakage is always positive with a tax credit. But domestic leakage with a mandate can be negative (in which case one energy-equivalent gallon of ethanol replaces more than one gallon of gasoline), making it possible that total leakage can be negative with a mandate. We also find that being a relatively smaller country in world oil markets does not automatically imply less leakage.

For the same quantity of ethanol, leakage due to a tax credit is always greater than that due to a binding consumption or blend mandate, while the combination of a binding mandate and a tax credit produces greater leakage than a mandate alone.

Our sensitivity analysis results show that one gasoline-energy equivalent gallon of ethanol replaces only 0.19 to 0.37 gallons of gasoline and the rest (0.81 to 0.63 gallons, respectively) is displaced. We find that U.S. corn ethanol does not meet the EPA’s sustainability standard even if the land use change effect is not considered. This makes the recent controversy over how to measure land use change inconsequential.

The significant fuel market leakage combined with the emissions from land use change make the situation even worse: one gallon of ethanol can emit as much as 16 percent more carbon than one gallon of gasoline. In one scenario – when oil supply in the rest of the world is very elastic relative to U.S. oil demand – we do find that a gasoline-energy equivalent gallon of ethanol offers a modest carbon reduction of 2.4 percent relative to gasoline. Thus, our key finding is that U.S. corn ethanol does not meet the EPA's 20 percent sustainability standard.

The empirical evidence presented in this paper suggests that market leakage from biofuel policies is significant. Leakage from biofuel policies is difficult to address in policy design, because even the superior (in terms of leakage) mandate does not decrease emissions much due to international leakage overriding the potentially negative domestic leakage. Leakage from biofuel policies is also a special problem from a policy standpoint because, unlike with leakage in a cap and trade policy or REDD scheme, the problem could not always be solved by having all countries adopt a biofuel policy. If all countries did coordinate, all leakage would be "autarky" leakage (i.e., all domestic) but this will likely result in little emissions savings compared to the case where the United States is the only country with the biofuel policy.

Appendix 1. Market Leakage due to a Blender's Tax Credit

Consider a binding blender's tax credit $\tilde{t}_c$ that determines the ethanol price $\tilde{P}_E$ (the tilde sign denotes prices expressed in dollars per gallon). The tax credit is a consumption subsidy that is paid to the fuel blender for each gallon of ethanol blended with gasoline. Following de Gorter and Just (2008) and assuming a zero fuel tax,[83] the market price for ethanol equals

$$\tilde{P}_E = \lambda P_G + \tilde{t}_c \tag{A1-1}$$

where λ denotes miles traveled per gallon of ethanol relative to gasoline and P_G denotes the price of gasoline. Dividing equation (A1-1) by λ, we express the ethanol market price P_E and the tax credit t_c in dollars per gasoline-equivalent gallon

$$P_E = P_G + t_c \tag{A1-2}$$

The intuition behind this relationship is as follows. The blenders compete for the tax credit until they bid up the price of ethanol to a level where it exceeds the gasoline price by the full amount of the tax credit.

We model ethanol and gasoline as perfect substitutes in consumption (adjusted for mileage). All ethanol is assumed to be produced and consumed in the Home country (*H*), while consumers in the Foreign country (*F*) consume only gasoline. The world fuel demand (*D*) equals the world fuel supply (*S*)

$$D_H(P_F) + D_F(P_G) = S_H(P_G) + S_F(P_G) + S_E(P_E) \tag{A1-3}$$

where P_F, denotes the price of fuel and S_E denotes supply of ethanol.

If the consumption of ethanol is not mandated, and consumers can choose a fuel by the mileage the fuel produces, then consumers are willing to buy ethanol only if the price of the fuel

[83] Adding a fuel tax to the model would make the formulae more complex with no qualitative change to the results.

blend (gasoline and ethanol) P_F equals the price of gasoline P_G; the latter must equal the ethanol market price P_E less the blender's tax credit t_c (see equation (A1-2))

$$P_F = P_G = P_E - t_c \tag{A1-4}$$

The system of equations (A1-2) to (A1-4) constitutes the market equilibrium under a binding tax credit. Totally differentiating this system, we obtain

$$\begin{gathered} dP_E = dP_G + dt_c \\ D_H' dP_F = \left(S_H' + S_F' - D_F'\right) dP_G + S_E' dP_E \\ dP_F = dP_G \end{gathered} \tag{A1-5}$$

where the prime (') denotes the derivative of a function with respect to its argument.

Solving the system (A1-5), we arrive at

$$\begin{gathered} \frac{dP_G}{dt_c} = \frac{S_E'}{D_H' + D_F' - S_H' - S_F' - S_E'} \leq 0, > -1 \\ \frac{dP_F}{dt_c} = \frac{S_E'}{D_H' + D_F' - S_H' - S_F' - S_E'} \leq 0, > -1 \\ \frac{dP_E}{dt_c} = \frac{D_F' + D_H' - S_H' - S_F'}{D_H' + D_F' - S_H' - S_F' - S_E'} \geq 0, \leq 1 \end{gathered} \tag{A1-6}$$

This means that the introduction of a tax credit by itself always reduces the world gasoline price and domestic fuel price by the same amount; however, the reduction is not as big as the tax credit itself. On the other hand, the tax credit always increases the ethanol market price by an amount smaller than the change in the tax credit (except if there is no pre-existing tax credit, when the increase is equal to the full amount of tax credit).

A change in the tax credit changes consumption of fuel in the Home and Foreign country and ethanol production as follows: $\frac{dD_H}{dt_c} = \frac{dD_H}{dP_F}\frac{dP_F}{dt_c}$; $\frac{dD_F}{dt_c} = \frac{dD_F}{dP_G}\frac{dP_G}{dt_c}$; $\frac{dS_E}{dt_c} = \frac{dS_E}{dP_E}\frac{dP_E}{dt_c}$. Note that $\frac{dD_H}{dP_F} = \eta_{DH}\frac{D_H}{P_F}$; $\frac{dD_F}{dP_G} = \eta_{DF}\frac{D_F}{P_G}$ and $\frac{dS_E}{dP_E} = \eta_{SE}\frac{S_E}{P_E}$, where $\eta_{DH}, \eta_{DF}, \eta_{SE}$ denote fuel demand elasticities in the Home and Foreign country and the (Home) ethanol supply elasticity, respectively.

Market leakage due to the tax credit L_M^τ is defined as a change in world fuel consumption divided by the amount of ethanol produced due to the tax credit

$$L_M^\tau = \frac{t_c \times \left.\frac{dD_H}{dt_c}\right|_{t_c=0} + t_c \times \left.\frac{dD_F}{dt_c}\right|_{t_c=0}}{t_c \times \left.\frac{dS_E}{dt_c}\right|_{t_c=0}} \tag{A1-7}$$

Note that for $t_c = 0$, we have $P_F = P_G = P_E$. Substitution of the derivatives in (A1-6) into expression (A1-7) yields the final expression for market leakage due to the tax credit

$$L_M^\tau = \frac{\rho\eta_{DH} + (1-\rho)\eta_{DF}}{\rho\eta_{DH} + (1-\rho)\eta_{DF} - \phi\eta_{SH} - (1-\phi)\eta_{SF}} \tag{A1-8}$$

where $\rho = D_H / (D_H + D_F)$ and $\phi = S_H / (S_H + S_F)$ denote consumption and production shares, respectively, of gasoline in the Home country before production of ethanol.

Appendix 2. Derivation of Elasticities of Excess Supply and Demand Curves

At a price P_G the Foreign country exports gasoline in the quantity of

$$X\left(P_G\right)=S_F\left(P_G\right)-D_F\left(P_G\right) \tag{A2-1}$$

Differentiating both sides of (A2-1) with respect to the price and manipulating, we obtain

$$\begin{aligned}
\frac{dX}{dP_G} &= \frac{dS_F}{dP_G}-\frac{dD_F}{dP_G} \\
\frac{dX}{dP_G}\frac{P_G}{X}\frac{X}{P_G} &= \frac{dS_F}{dP_G}\frac{P_G}{S_F}\frac{S_F}{P_G}-\frac{dD_F}{dP_G}\frac{P_G}{D_F}\frac{D_F}{P_G} \\
\eta_{ES} &= \eta_{SF}\frac{S_F}{X}-\eta_{DF}\frac{D_F}{X} \\
\eta_{ES} &= \eta_{SF}\frac{S_F}{S_F-D_F}-\eta_{DF}\frac{D_F}{S_F-D_F}
\end{aligned} \tag{A2-2}$$

where η_{ES} denotes the elasticity of excess supply.

Multiplying both the numerator and the denominator of (A2-2) by $\frac{1}{D_H+D_F}$, which is also equal to $\frac{1}{S_H+S_F}$, we obtain

$$\eta_{ES}=\eta_{SF}\frac{1-\phi}{\rho-\phi}-\eta_{DF}\frac{1-\rho}{\rho-\phi} \tag{A2-3}$$

where the definition of ρ and ϕ is the same as in Appendix 1. Similarly, for the excess demand curve we obtain

$$\eta_{ED}=\eta_{DH}\frac{\rho}{\rho-\phi}-\eta_{SH}\frac{\phi}{\rho-\phi} \tag{A2-4}$$

Therefore, a small importer faces a perfectly elastic excess supply curve when $\eta_{SF}\to\infty$; a small exporter faces a perfectly elastic excess demand curve when $\eta_{DH}\to-\infty$; and irrespective of the trade position, a small country faces a perfectly elastic trade curve whenever $\rho\to\phi$ (the case analyzed in the paper).

Appendix 3. Market Leakage due to a Consumption Mandate

We specify here a full model of a consumption mandate combined with a tax credit. The results for a mandate alone are readily obtained by setting $t_c = 0$. All quantities and prices are measured in gasoline equivalents. The world fuel market equilibrium with a binding consumption mandate and a blenders' tax credit (both in the Home country) is given by

$$\begin{gathered}
\bar{E} = S_E(P_E) \\
D_H(P_F) + D_F(P_G) = S_H(P_G) + S_F(P_G) + \bar{E} \\
P_F = \frac{\bar{E}}{D_H(P_F)}(P_E - t_c) + \left(1 - \frac{\bar{E}}{D_H(P_F)}\right)P_G
\end{gathered} \tag{A3-1}$$

where $\bar{E}$ represents the mandated quantity of ethanol. The remaining notation is the same as in Appendix 1. The first two equations in (A3-1) are self-explanatory; the third represents an equilibrium condition where the blender equilibrates his marginal cost with the market fuel price. The marginal cost is given by a weighted average of ethanol and gasoline prices where the weights are formed by the share of the mandated quantity of ethanol in the endogenous amount of fuel.

Totally differentiating the system (A3-1), we obtain

$$\begin{gathered}
d\bar{E} = S_E' dP_E \\
D_H' dP_F = (S_H' + S_F' - D_F')dP_G + d\bar{E} \\
\left(D_H + (P_F - P_G)D_H'\right)dP_F = (P_E - t_c - P_G)d\bar{E} + \bar{E}dP_E - \bar{E}dt_c + \left(D_H - \bar{E}\right)dP_G
\end{gathered} \tag{A3-2}$$

where the prime (') denotes the derivative of a function with respect to its argument.

Solving the system (A3-2), we arrive at

$$\frac{dP_E}{d\bar{E}} = \frac{1}{S_E'} > 0$$

$$\frac{dP_G}{d\bar{E}} = \frac{\left(P_E - t_c - P_F + \frac{\bar{E}}{S_E'} - \frac{D_H}{D_H'}\right)D_H'}{\left(D_H + \left(P_F - P_G\right)D_H'\right)\left(S_H' + S_F' - D_F'\right) - \left(D_H - \bar{E}\right)D_H'} < 0; \text{for } \eta_{DH} > -1 \qquad \text{(A3-3)}$$

$$\frac{dP_F}{d\bar{E}} = \frac{\left(S_{HG}' + S_{FG}' - D_F'\right)\left(P_E - t_c - P_F + \frac{\bar{E}}{S_E'} - \frac{D_H}{D_H'}\right)}{\left(D_H + \left(P_F - P_G\right)D_H'\right)\left(S_H' + S_F' - D_F'\right) - \left(D_H - \bar{E}\right)D_H'} + \frac{1}{D_H'} >, < 0$$

and

$$\frac{dP_E}{dt_c} = 0$$

$$\frac{dP_G}{dt_c} = \frac{\bar{E}D_H'}{\left(D_H - \bar{E}\right)D_H' - \left(S_H' + S_F' - D_F'\right)\left(D_H + \left(P_F - P_G\right)D_H'\right)} > 0 \text{ for } \eta_{DH} > -1 \qquad \text{(A3-4)}$$

$$\frac{dP_F}{dt_c} = \frac{\bar{E}\left(S_H' + S_F' - D_F'\right)}{\left(D_H - \bar{E}\right)D_H' - \left(S_H' + S_F' - D_F'\right)\left(D_H + \left(P_F - P_G\right)D_H'\right)} < 0 \text{ for } \eta_{DH} > -1$$

The first set of derivatives (A3-1) reveals that the ethanol market price increases when the consumption mandate increases, while the world price of gasoline decreases. A change in the mandate has an ambiguous impact on the final fuel price in the Home country. The change in the Home country fuel price heavily depends on supply and demand elasticities in both countries, as well as on gasoline consumption and production shares in both countries.

The second set of derivatives(A3-4) posits that, with a pre-existing binding consumption mandate, a change in the tax credit has no effect on the ethanol market price (because this price is determined by the intersection of the ethanol supply curve and the perfectly inelastic demand for ethanol by blenders, which correspond to the mandate level). An increase in the tax credit does, however, increase the gasoline price. This happens because the tax credit acts as a consumption subsidy, thus lowering the fuel price (see the last derivative in (A3-4)) which translates into higher fuel consumption in the Home country. Since the quantity of ethanol is fixed by the mandate, the additional fuel comes in the form of gasoline; the increase in gasoline consumption leads to an increase in the gasoline price.

Market leakage due to a consumption mandate alone, denoted by L_M^σ, is given by the change in global fuel consumption (due to a consumption ethanol mandate) divided by the mandated level of ethanol. It can be expressed as

$$L_M^\sigma = \frac{\bar{E} \times \left.\frac{dD_H}{d\bar{E}}\right|_{\bar{E}=0,t_c=0} + \bar{E} \times \left.\frac{dD_F}{d\bar{E}}\right|_{\bar{E}=0,t_c=0}}{\bar{E}} = \left.\frac{dD_H}{dP_F}\frac{dP_F}{d\bar{E}}\right|_{\bar{E}=0,t_c=0} + \left.\frac{dD_F}{dP_G}\frac{dP_G}{d\bar{E}}\right|_{\bar{E}=0,t_c=0} \qquad \text{(A3-5)}$$

Evaluating the derivatives in (A3-3) at $\bar{E} = 0$ and $t_c = 0$ and substituting then into (A3-5), after some manipulations we arrive at the expression for the market leakage due to a consumption mandate

$$L_M^\sigma = \frac{(\delta - 1)\eta_{DH}\left(\phi\eta_{SH} + (1-\phi)\eta_{SF}\right) - \rho\eta_{DH} - (1-\rho)\eta_{DF}}{\phi\eta_{SH} + (1-\phi)\eta_{SF} - \rho\eta_{DH} - (1-\rho)\eta_{DF}} \qquad \text{(A3-6)}$$

where $\delta = P_E / P_G$ denotes the ratio of the intercept of the ethanol supply curve and the gasoline price in the absence of the mandate; the rest of the notation is the same as in Appendix 1.

Finally, from the system (A3-2) it follows that a change in the gasoline price when both the mandate and tax credit are changed simultaneously is given by

$$\begin{aligned} dP_G = &\frac{(P_E - t_c - P_G)D_H'S_E' + \bar{E}D_H' - \left(D_H + (P_F - P_G)D_H'\right)S_E'}{(S_H' + S_F' - D_F')\left(D_H + (P_F - P_G)D_H'\right)S_E' - \left(D_H - \bar{E}\right)D_H'S_E'} d\bar{E} \\ &- \frac{\bar{E}D_H'}{(S_H' + S_F' - D_F')\left(D_H + (P_F - P_G)D_H'\right) - \left(D_H - \bar{E}\right)D_H'} dt_c \end{aligned} \qquad \text{(A3-7)}$$

For Result 3, we need to determine the sign of (A3-7) when both policies are introduced

$$\left. dP_G \right|_{\bar{E}=0,t_c=0} = \frac{(P_E - P_G)D_H' - D_H}{(S_H' + S_F' - D_H' - D_F')D_H} d\bar{E} < 0 \qquad \text{(A3-8)}$$

Appendix 4. Model for a Blend Mandate

The world fuel market equilibrium with a binding blend mandate α and a blender's tax credit t_c in the Home country is given by

$$\begin{gathered} S_E\left(P_E\right)=\alpha D_H\left(P_F\right) \\ D_H\left(P_F\right)+D_F\left(P_G\right)=S_H\left(P_G\right)+S_F\left(P_G\right)+S_E\left(P_E\right) \\ P_F=\alpha\left(P_E-t_c\right)+\left(1-\alpha\right)P_G \end{gathered} \tag{A4-1}$$

where the notation is the same as in Appendix 1. The first equation in (A4-1) posits that the quantity of ethanol produced is equal to the mandated share of total fuel consumption in the Home country; the second equation represents the world fuel equilibrium; the third equation equilibrates the fuel market price with the blender's marginal cost.

Totally differentiating the system (A4-1) and solving it, we obtain

$$\frac{dP_G}{d\alpha}=\frac{P_E-t_c-P_G+\alpha\dfrac{D_H}{S_E'}-\left(1-\alpha^2\dfrac{D_H'}{S_E'}\right)\dfrac{D_H}{(1-\alpha)D_H'}}{\left(1-\alpha^2\dfrac{D_H'}{S_E'}\right)\dfrac{(S_H'+S_F'-D_F')}{(1-\alpha)D_H'}+\alpha-1}<0$$

$$\frac{dP_F}{d\alpha}=\frac{\left(S_H'+S_F'-D_F'\right)\left(P_E-t_c-P_G+\alpha\dfrac{D_H}{S_E'}-\left(1-\alpha^2\dfrac{D_H'}{S_E'}\right)\dfrac{D_H}{(1-\alpha)D_H'}\right)}{(1-\alpha)\left(\left(1-\alpha^2\dfrac{D_H'}{S_E'}\right)\dfrac{(S_H'+S_F'-D_F')}{(1-\alpha)D_H'}+\alpha-1\right)D_H'}+\frac{D_H}{(1-\alpha)D_H'}>,<0$$

$$\frac{dP_E}{d\alpha}=\frac{D_H}{S_E'}+\frac{\alpha}{S_E'}\left(\frac{\left(S_H'+S_F'-D_F'\right)\left(P_E-t_c-P_G+\alpha\dfrac{D_H}{S_E'}-\left(1-\alpha^2\dfrac{D_H'}{S_E'}\right)\dfrac{D_H}{(1-\alpha)D_H'}\right)}{(1-\alpha)\left(\left(1-\alpha^2\dfrac{D_H'}{S_E'}\right)\dfrac{(S_H'+S_F'-D_F')}{(1-\alpha)D_H'}+\alpha-1\right)}+\frac{D_H}{(1-\alpha)}\right)>,<0$$

(A4-2)

$$\frac{dP_G}{dt_c} = \frac{\alpha}{1-\alpha-\left(1-\alpha^2\frac{D_H'}{S_E'}\right)\frac{\left(S_H'+S_F'-D_F'\right)}{(1-\alpha)D_H'}} > 0$$

$$\frac{dP_F}{dt_c} = \frac{\alpha\left(S_H'+S_F'-D_F'\right)}{(1-\alpha)^2 D_H' - \left(1-\alpha^2\frac{D_H'}{S_E'}\right)\left(S_H'+S_F'-D_F'\right)} < 0 \qquad \text{(A4-3)}$$

$$\frac{dP_E}{dt_c} = \frac{\alpha^2\left(S_H'+S_F'-D_F'\right)D_H'}{\left((1-\alpha)^2 D_H' - \left(1-\alpha^2\frac{D_H'}{S_E'}\right)\left(S_H'+S_F'-D_F'\right)\right)S_E'} > 0$$

The first set of derivatives (A4-2) reveals that gasoline price always decreases with an increase in the blend mandate, but the effect of such an increase on fuel and ethanol prices is ambiguous. The ambiguity of the effect of a change in the blend on the ethanol price occurs because the ethanol price is linked to the fuel price through the first equation in (A4-1).

The intuition for the signs of the first two derivatives in (A4-3) is the same as for the consumption mandate. In addition, the ethanol price increases with an increase in the tax credit because the tax credit lowers the fuel price which leads to higher fuel consumption and hence higher ethanol production. Increased ethanol production can only be achieved through a higher market price of the biofuel.

Finally, it follows that a change in the gasoline price when both the mandate and tax credit are changed simultaneously is given by

$$dP_G = \frac{P_E - t_c - P_G + \alpha\frac{D_H}{S_E'} - \left(1-\alpha^2\frac{D_H'}{S_E'}\right)\frac{D_H}{(1-\alpha)D_H'}}{\left(1-\alpha^2\frac{D_H'}{S_E'}\right)\frac{\left(S_{HG}'+S_{FG}'-D_F'\right)}{(1-\alpha)D_H'}+\alpha-1}d\alpha - \frac{\alpha}{\left(1-\alpha^2\frac{D_H'}{S_E'}\right)\frac{\left(S_{HG}'+S_{FG}'-D_F'\right)}{(1-\alpha)D_H'}+\alpha-1}dt_c$$

(A4-4)

For Result 4, we need to determine the sign of (A4-4) when both policies are introduced

$$dP_G\big|_{\alpha=0,t_c=0} = \frac{\left(P_E-P_G\right)D_H'-D_H}{S_{HG}'+S_{FG}'-D_H'-D_F'}d\alpha < 0 \qquad \text{(A4-5)}$$

Appendix 5. Data Used to Calibrate the Model

Variable/parameter	Symbol	Value	Unit	Source
PARAMETERS				
Miles per gallon of ethanol relative to gasoline	λ	0.69		Cui et al. (2011)
Ethanol produced from one bushel of corn	β	2.80	gallon/bushel	Eidman (2007)
DDGS production coefficient [a]	γ	17/56		Eidman (2007)
DDGS relative price to corn	r	0.86		$r = (P_C*56)/(P_{DDGS}*2000)$
Gasoline production coefficient	β_G	21.48	gallon/barrel	$\beta_G = G/Q^H_O$
Petroleum by-product production coefficient	β_B	23.29	GEEG/barrel [b]	$\beta_B = 42*1.066 - \beta_G$
Price and quantity link between corn and ethanol market	k	2.61	GEEG/bushel	$k = \lambda\beta/(1-r\gamma)$
Ratio of additives to gasoline	K	0.09		$K = A/G$
Ethanol processing cost	c^E_0	1.36	$/GEEG	$c^E_0 = P_E + s_E/\lambda - P_C/k$
Gasoline processing cost	c^G_0	0.83	$/GEEG	$c^G_0 = P_G + \beta_B P_B/\beta_1 - P_O/\beta_G$
Share of domestic consumption of DDGS	ω	0.81		Hoffman and Baker (2011)
POLICY VARIABLES				
Blend mandate [c]	α	0.06		$\alpha = E/F$
Ethanol tax credit	t_c	0.50	$/gallon	t_c = \$0.45/gal. + \$0.048/gal. [d]
Ethanol production subsidy	s_E	0.14	$/gallon	Assumed to be the same as in 2008 [e]
Corn production subsidy	s_C	0.17	$/bushel	Environmental Working Group [f]
Fuel tax	t	0.49	$/gallon	American Petroleum Institute [g]
Tax on petroleum by-products	t_B	0.16	$/gallon	$t_B = 0.33*t$
PRICES				
Oil price	P_O	61.00	$/barrel	Cui et al. (2011)
Gasoline price	P_G	1.76	$/gallon	Gasoline average rack price in Omaha, Nebraska [h]
Ethanol market price (volumetric)	P_e	1.79	$/gallon	Ethanol average rack price in Omaha, Nebraska [h]
Ethanol market price (energy)	P_E	2.59	$/GEEG	$P_E = P_e/\lambda$
Ethanol producer price	P^P_E	2.79	$/GEEG	$P^P_E = P_E + s_E/\lambda$
Fuel price	P^F	2.27	$/GEEG	$P_F = \alpha*(P_E + t/\lambda + t_c/\lambda) + (1-\alpha)*(P_G + t)$
Market price of petroleum by-products	P_B	1.76	$/GEEG	Cui et al. (2011)
Consumer price of petroleum by-products	P^C_B	1.92	$/GEEG	$P^C_B = P_B + t_B$
Corn market price	P_C	3.75	$/bushel	USDA [i]
Corn producer price	P^P_C	3.92	$/bushel	$P^P_C = P_C + s_C$
DDGS price	P_{DDGS}	114.38	$/ton	USDA [j]

Notes:

[a] DDGS = Dried distillers grains with solubles

[b] GEEG = Gasoline-energy equivalent gallon

[c] The blend mandate is expressed in energy terms.

[d] \$0.45/gallon is the federal component of the tax credit; the \$0.048/gallon is the average state tax credit reported by Koplow (2009).

[e] Koplow (2009) estimates the U.S. ethanol production subsidies in 2008 to be \$1.356 billion. Ethanol production in 2008 reached 9.6579 billion gallons (EIA).

[f] http://farm.ewg.org/progdetail.php?fips=00000&progcode=corn (For details on the calculation of the corn subsidy, see the text of the paper).

[g] http://www.api.org/statistics/fueltaxes/upload/gasoline-diesel-summary.pdf (average for 2009)

[h] http://www.neo.ne.gov/statshtml/66.html

[i] http://www.ers.usda.gov/data-products/feed-grains-database/feed-grains-yearbook-tables.aspx

[j] http://www.ers.usda.gov/data-products/feed-grains-database/feed-grains-yearbook-tables.aspx#26818

Appendix 5. Data Used to Calibrate the Model (continued)

Variable/parameter	Symbol	Value	Unit	Source
QUANTITIES				
World oil production	S^W_O	26.38	billion barrels	EIA [k]
Domestic oil supply	S^H_O	1.99	billion barrels	EIA [l]
Oil supply in the Rest of the world	S^F_O	24.40	billion barrels	$S^F_O = S^W_O - S^H_O$
Oil consumption in the Rest of the world	D^F_O	21.12	billion barrels	$D^F_O = S^W_O - S^H_O - S^M_O$
U.S. oil imports	S^M_O	3.27	billion barrels	EIA [l]
Total oil available in the United States	Q^H_O	5.26	billion barrels	$Q^H_O = S^H_O + S^M_O$
Quantity of petroleum by-products	Q_B	122.48	billion GEEGs	$Q_B = \beta_B Q^H_O$
Consumption of petroleum by-products	C_B	122.48	billion GEEGs	$C_B = Q_B$
Fuel demand (volumetric)	f	134.75	billion gallons	EIA [l]
Fuel demand (energy)	F	131.34	billion GEEGs	F = G + A + E
Ethanol consumption (volumetric)	e	11.04	billion gallons	EIA [l, m]
Ethanol consumption (energy)	E	7.63	billion GEEGs	$E = \lambda e$
Gasoline supply	G	112.98	billion gallons	G = f - A - e
Imports of fuel additives	A	10.73	billion gallons	EIA [l]
Domestic corn supply	S^H_C	13.09	billion bushels	Cui et al. (2011)
Domestic yellow corn demand as food/feed	D^H_C	7.29	billion bushels	$D^H_C = S^H_C - Q'_C - D^F_C$
Foreign yellow corn import demand	D^F_C	1.86	billion bushels	Cui et al. (2011)
Corn used in ethanol production (initial) [n]	Q_C	2.92	billion bushels	$Q_C = E/k$
Corn used in ethanol production (equilibrium) [o]	Q'_C	3.94	billion bushels	$Q'_C = Q_C/(1-r\gamma)$
DDGS supply	DDGS	1.02	billion bushels	$DDGS = r\gamma Q'_C$
Quantity of domestic DDGS consumption	$DDGS^H$	0.83	billion bushels	$DDGS^H = \omega * DDGS$
Quantity of DDGS exports	$DDGS^F$	0.19	billion bushels	$DDGS^F = (1-\omega) * DDGS$
U.S. domestic consumption of non-ethanol corn-equivalent	D'^H_C	8.12	billion bushels	$D'^H_C = D^H_C + DDGS^H$
U.S. exports of corn equivalent	D'^F_C	2.06	billion bushels	$D'^F_C = D^F_C + DDGS^F$
ELASTICITIES				
Domestic supply elasticity of oil	η^H_{SO}	0.20		Cui et al. (2011)
Import supply elasticity of oil	η^M_{SO}	3.00		Cui et al. (2011)
Domestic supply elasticity of corn	η^H_{SC}	0.23		Gardner (2007)
Domestic demand elasticity of corn	η^H_{DC}	-0.20		Cui et al. (2011)
Foreign demand elasticity of corn	η^F_{DC}	-1.50		Cui et al. (2011)
Domestic demand elasticity of fuel	η^H_{DF}	-0.26		Hamilton (2009)
Domestic demand elasticity of petroleum by-products	η^H_{DB}	-0.26		Assumed to be the same as η^H_{DF}
ROW oil supply elasticity	η^F_{SO}	0.15		Assumed
Demand elasticity of oil in the Rest of the world	η^F_{DO}	-0.29		$\eta^F_{DO} = (S^M_O/D^F_O)*(\eta^F_{SO}*(S^F_O/S^M_O)-\eta^M_{SO})$

Notes:

[k] http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=5&pid=57&aid=1&cid=ww,&syid=2009&eyid=2009&unit=TBPD

[l] http://www.eia.gov/forecasts/steo/query/

[m] Ethanol consumption is assumed to be equal to ethanol production.

[n] This quantity of corn does take into account the market effects of DDGS.

[o] This quantity of corn takes into account the market effects of DDGS.

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