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ABSTRACT

We develop an analytical framework to assess the market effects of alternative biofuel policies (including subsidies to feedstocks). U.S. corn-ethanol policies are used as an example to study the effects 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 policy; and generalize the unique 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 by-product, the value of production subsidies, and where the world ethanol price is determined. U.S. corn-ethanol policies are a major reason for the increases in corn prices – an estimated increase of 26 – 45% in the period 2008 – 2011.

Key words: biofuel policies, corn prices, tax credit, mandate, ethanol subsidy, corn subsidy, water, price premium

JEL Classification: Q02, Q18, Q19

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 it can be applied to any country or biofuel policies. 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) the determination of the 'no policy' ethanol price; (2) the implications for the 'no policy' corn price and resulting 'water' in the ethanol price premium due to policy;[2] and (3) and 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 recent grain price increase is that biofuel policies are only one of a multitude of contributing factors. Typical studies include Headey and Fan (2010) who attribute the price increase to a "near-perfect storm" of factors, or Abbott et al. (2008, 2009), who argue it has been a "complex maze of factors" where "one cannot with any precision partition the effects" and although biofuels is one "driver" of many, only 25 percent of biofuels contribution to the price rise is due to biofuel policy.[4] However, Wright (2011) argues that most of the factors falling under the rubric of a "near-perfect storm" do not in the aggregate explain the recent grain price spikes. He concludes the two recent grain price spikes were due to a new demand for biofuels.

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[1] The paper represents work in progress and comments are very welcome.
[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.

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 – under alternative policies – among biofuels, their feedstocks and fossil fuel (oil). It also provides the means to determine whether 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 by product in modeling the price (i.e., vertical) and quantity (i.e., horizontal) links between the fuel and corn markets. Because the ethanol by-product (Dried Distillers Grains with Solubles) is a very close substitute to yellow corn in feed consumption, when returned to the corn market it replaces yellow corn, making it possible for the ethanol industry to obtain effectively more feedstock than initially available. We call this the recycling effect of the ethanol by-product. This has important implications not only for the ethanol supply curve *per se* – it is more elastic than thought – but also for the analysis of the price effects of biofuel policies and 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 extensively study the corn price effects of the remaining four biofuel policies (blend mandate, blender's tax credit, ethanol and corn production subsidies) alone and their interactions. We find that if the biofuel mandate binds, that is, determines the

[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).

ethanol market price, the other three subsidies (where the tax credit is an ethanol consumption subsidy) subsidize fuel, and hence gasoline consumption. However, the market mechanism differs in their effects on ethanol and corn price. For example, a tax credit increases the ethanol market price, while the ethanol production subsidy reduces it; nevertheless, both make the corn market price rise.

Third, we revisit the concept of 'water' in biofuel policy where the intercept of the ethanol supply curve is above the ethanol price that would occur without the four policies under consideration. We find that the previous literature has omitted the effect of the volumetric fuel tax on 'water', thus significantly underestimating the rectangular deadweight costs of biofuel policies, by 80 – 120 percent. 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 render consumers to purchase ethanol under no biofuel policy, is high because of (1) lower mileage per gallon of ethanol relative to gasoline and (2) a penalty due to the volumetric fuel tax. For example, we estimate the price premium to be \$3.58/bu in 2008, or 56 percent of the ethanol market price. However, the impact of the price premium on corn market prices is much lower because of existing water, implying that the impact of biofuel policies, although significant, is not as big as could have been if there had been less water.

The paper is outlined as follows. The next section develops the link between ethanol and corn prices (vertical link). The link between corn and ethanol quantities (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 both on 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 all of our theoretical results. The last section provides concluding remarks.

2. The Link between Ethanol and Corn Prices

One bushel of yellow corn produces β = 2.8 gallons of ethanol (Eidman 2007). The lower energy content of ethanol relative to gasoline is reflected in relative miles traveled per gallon, meaning that one gallon of ethanol yields only λ = 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-equivalent gallons (GEGs) of ethanol.

Associated with a bushel of yellow corn processed into ethanol are γ = 0.304 bushels of a by-product known as Dried Distillers Grains with Solubles (DDGS) (Eidman 2007). The DDGS are a valuable substitute for yellow corn in non-ethanol consumption, especially as an animal feed. The market price of the by-product typically differs from that of yellow corn. We denote this price as $r \times P_C$, where r represents a relative price of the by-product and yellow corn, the latter denoted by P_C. Let the processing cost of one GEG of ethanol be c_0. Following de Gorter and Just (2008) and Cui et al. (2011), we assume c_0 does not vary with the quantity of ethanol produced. Ethanol is assumed to be produced by perfectly competitive firms using a constant returns to scale technology. The assumptions about the technology and market structure imply zero marginal profits, in equilibrium, expressed per GEG of ethanol[7]

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

[6] Using average EPA data, de Gorter and Just take into account of the difference in comparing 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 λ = 0.7. If one simply uses the differential energy content, then the value of λ = 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] See Mallory et al. (2010) for the justification for the zero-profit condition.

where P_E denotes the ethanol price per GEG received by ethanol producers.[8] Expressing the corn price from equation (1) yields[9]

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

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

How Well Does the Theoretical Corn-Ethanol Price Conversion Factor 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 a few past years reveal that ethanol producers earn (mostly) positive profits. Given this discrepancy, which can be either due to a short operation period of ethanol plants, or due to a measurement error, any further analysis requires a comparison of how well the theoretical corn price predicts reality.

The first column of Table 1 shows the average annual profits of ethanol production per gallon. We use monthly data (March 2005 to June 2011) for ethanol operating margins reported by CARD of Iowa State University.[10] The profits were significantly positive in the first three years when many ethanol production facilities emerged. Overall, however, the profit margins tend to decline, reaching almost zero levels in 2010 and 2011. To test the validity of the relationship (2) empirically, we rewrite it as

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[8] Typically, this price is equal to the ethanol market price; however, when there is an ethanol production subsidy, it would be equal to the sum of the ethanol market price and the production subsidy.

[9] 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 is then given by: $P_C = \left(\lambda\beta P_E - \tilde{c}_0\right)/\left(1 - r\gamma\right)$. Comparing the forgoing expression with that in equation (2), yields: $\tilde{c}_0 = \lambda\beta c_0$.

[10] http://www.card.iastate.edu/research/bio/tools/hist_eth_gm.aspx

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

where the left-hand side of equation (3) is solely determined by the observables, while the right-hand side consists of fixed parameters[11], except for the relative price of DDGS to ethanol r because this may vary over time. As the CARD does not report prices for DDGS, we use the 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 (averaging \$0.52 per gallon over the period of observation). All data reported in Table 1 pertain to a gallon of ethanol not adjusted for the energy content. In order to obtain their gasoline-equivalent counterparts, the values in the first column need to be divided, and those in the remaining columns 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 representing the predicted vertical (i.e., price) ethanol-corn conversion factor. The discrepancies are comparatively large, especially for 2005 to 2007. The reason is the observed non-zero profits. Since 2008 the values in the second and forth columns get much closer because profits are very close to zero. Indeed, if the observed profits are a measurement error, and we adjust the left-hand side of equation (3) for it (column 3), then in the period 2008 – 2011 (highlighted) both sides of equation (3) are almost the same.[12] The remaining discrepancies are attributable to different locations for the corn and DDGS prices – Iowa and Indiana, respectively. Given the good match between the predicted and observed corn prices in the period 2008 – 2011, we use these years in our empirical analysis.

[11] These parameters are assumed to be fixed at least over the period analyzed.

[12] Mallory et al. (2010) propose that the link between the corn and the energy sectors is manifested in futures prices at least one year to maturity. Although we use spot prices to test the predictive ability of equation (2), we obtain a close match between the predicted and observed prices. Moreover, our numerical simulations are only meant to illustrate the magnitudes of the market effects, not to predict the corn price per se.

3. The Link between Ethanol and Corn Quantities

We showed above that, under some plausible assumptions, a long run relationship between corn and ethanol prices can be expected. To derive that price link, we assumed 2.8 gallons of ethanol (1.96 GEGs) are produced from one bushel of yellow corn. But is this technological parameter *the* conversion factor that governs the quantity link between the corn and ethanol market? The answer is negative if one considers only the intended amount of corn to be used in ethanol production; but it is affirmative if we analyze the observed amount of corn used in ethanol production. The reason is quite intuitive: because DDGSs are a very close substitute to yellow corn in feed/food consumption, a market effect of the ethanol by-product is to replace yellow corn that would otherwise be consumed outside of the ethanol sector; thus, making more yellow corn available for ethanol production. This means that one bushel of yellow corn effectively produces more than 2.8 gallons of ethanol. We call this the *recycling effect* of the ethanol by-product. On the other hand, a ratio of ethanol production and the amount 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 a 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 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 latter represents aggregate (domestic and export) demand for feed/food corn facing U.S. farmers. At a corn price above P_{NE}, there is an excess supply of yellow corn – feedstock for ethanol production. Note that because yellow corn and the ethanol by-product are very close substitutes, the demand curve D_{NE} can also be thought of as demand for a mixture of yellow corn and

DDGSs. It means that in the absence of ethanol production D_{NE} denotes demand for yellow corn; but if ethanol is produced, D_{NE} represents total demand for both forms of corn.

Assume an ethanol blender's tax credit $\tilde{t}_c$ determines the ethanol market price $\tilde{P}_E$, where the tilde sign denotes that the blender's tax credit and ethanol market price are expressed in dollars per gallon of ethanol. Following de Gorter and Just (2008), 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)[13] and t is a volumetric fuel tax. Dividing equation (4) by λ, we express the prices in dollars per GEG (similarly to Cui et al. 2011)

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

where $P_E = \tilde{P}_E/\lambda$ and $t_c = \tilde{t}_c/\lambda$. Ethanol market price given by equation (5) is depicted in the second panel of Figure 1 (also in Figures 2 and 3).[14] The idea behind equations (4) and (5) is that if consumers are free to choose a fuel to purchase, and if they buy a fuel based on the miles traveled, then they will buy ethanol only if its price (adjusted for the fuel tax and tax credit) per GEG equals that of gasoline. (See section 5 for a more detailed discussion).

Corresponding to the ethanol price P_E (equal to the ethanol market price plus an ethanol production subsidy, if any) is the corn price P_C, equal to the price of ethanol in dollars per bushel, P_{Eb}.[15] If the corn market price is linked to the ethanol price through equation (2) and the latter is linked to the oil price – as is the case when the U.S. tax credit is determining the ethanol

[13] For simplicity, we assume an exogenous gasoline (oil) price. The full model with an endogenous gasoline price is presented in appendices.

[14] In our graphical analysis, we assume, for simplicity that the gasoline supply is perfectly elastic. We relax this assumption in the appendices, however.

[15] To avoid the "discontinuities" along the vertical axis in the second panel of the figures (that occur because the conversion factor between ethanol and corn prices is higher than one), we assume that the corn market price equals ethanol price received by ethanol producers. This simplifies the exposition but has no impact on the results.

price – then any supply/demand shifts[16] are academic and have no effect on the corn price (unless they affect oil prices). The only thing these shifts do 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 level of 'water'[17] in the ethanol price premium due to the tax credit. This point seems to be forgotten in the debate about the role of the ethanol tax credit or ethanol price premium due to the mandate in affecting corn prices.

The amount of yellow corn produced at price P_C is Q_C and the amount to be consumed (in non-ethanol industries) is C_{NE}.[18] Thus, for any price P_C – linked to the ethanol price – the horizontal difference between S_C and D_{NE} in the first panel of Figure 1 represents an amount of yellow corn for ethanol production. Multiplying this quantity by the parameter $\beta = 2.8$, we obtain a corresponding ethanol supply curve S_{E0}, constructed under the assumption of no by-product. Note that the intercept of S_{E0}, adjusted for units, corresponds to P_{NE}. In this situation, the amount of ethanol is Q_{E0}, equal to β times the distance $C_{NE}Q_C$ in the first panel of Figure 1. But there inevitably is a by-product of ethanol production, and it needs to be taken into consideration when modeling the corn market.

The high degree of substitutability of DDGSs for yellow corn implies a one-to-one replacement of yellow corn – that would otherwise be consumed as a feed – with the ethanol by-product.[19] We term this as the recycling effect of the ethanol by-product. Because of the recycling effect, additional yellow corn is made available for ethanol production. This process

[16] These shifts can be, for example, due to exchange rate depreciation, bad weather, income growth in developing countries, or biodiesel mandates that increase the soybean prices (Heady and Fan, 2010; Abbott et al., 2008, 2009; Hochman et al. 2011).
[17] The concept of 'water' in a biofuel policy is explained in section 5.
[18] At this stage, we aim to determine the amount of yellow corn to be used in ethanol production at price P_E. When ethanol is produced and the by-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.
[19] In reality, the market does not always value DDGSs as a perfect substitute for yellow corn because the market price of DDGS is not always equal to price of corn. We capture this by considering the relative price of DDGS and corn in equation (2).

continues until the marginal increment in yellow corn that could be used for ethanol is zero.[20] In equilibrium, one initial bushel of corn is associated with $1/(1-\gamma) \approx 1.44$ bushels of yellow corn processed for ethanol. By definition, the size of the recycling effect is equal to the total amount of the by-product in equilibrium; that is, $\gamma/(1-\gamma) = 0.44$ additional bushels of corn are associated with one initial bushel of corn.[21]

Accounting for the recycling effect, one bushel of corn yields $\lambda\beta/(1-\gamma) = 2.82$ gasoline-equivalent gallons of ethanol.[22,23] Therefore, the equilibrium supply of ethanol, denoted by S_{E1} in the second panel of Figure 1, is given by

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

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 horizontally subtracting the amount of the by-product from D_{NE} at any corn price above P_{NE}. By construction, D_{NEY} is more elastic relative to D_{NE}.

[20] Mathematically, denote X as the initial amount of yellow corn for ethanol production. The amount of the by-product is then γX which replaces yellow corn one-to-one, thus generating additional γX bushels of yellow corn. This conversion process continues until the amount of additional yellow corn approaches zero in the limit. As a result, the total amount of yellow corn actually used in ethanol consumption is $X + \gamma X + \gamma^2 X + ... = X/(1-\gamma)$. This process is bound to converge because its quotient satisfies $0 < \gamma < 1$.

[21] The analysis above needs to be adjusted if there is an upper bound on the share of the by-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 by-product satisfies: $\gamma \times \left(S_C(P_C) - D_{NE}(P_C)\right)/D_{NE}(P_C) < \bar{\theta}$, 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: $\gamma \times \left(S_C(P_C) - D_{NE}(P_C)\right)/D_{NE}(P_C) \geq \bar{\theta}$, then the technological constraint binds, and the maximum quantity of ethanol produced is: $\lambda\beta \times \left(\bar{\theta} D_{NE}(P_C) + \left(S_C(P_C) - D_{NE}(P_C)\right)\right)$, which is always less than the quantity given by identity (7). Whether the constraint is binding or not is an empirical question.

[22] If not adjusted for the relative miles traveled per gallon of ethanol and gasoline, one bushel of yellow corn produces 2.8/(1-0.304) = 4.02 gallons of ethanol.

[23] Note that Cui et al. (2011) use the same conversion factor both for prices and quantities.

Alternatively, the effects of the by-product on the corn market can be viewed as a pivot of the corn supply curve S_C. DDGSs increase the supply of corn expressed in corn-equivalent. Thus, the curve S_{CE} in the first panel of Figure 1 denotes the amount 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 by-product. Mathematically,

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

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.

Close inspection of relationships (2) and (6) suggests that biofuel policies and/or policies in the corn market affect ethanol production or corn production/consumption indirectly: ethanol prices affect corn prices; these have an effect on corn production and feed/food consumption. This in turn determines the amount of ethanol produced. Note also the slight difference in the conversion factor for prices and quantities – horizontal and vertical distance in all figures. While the vertical factor contains r, the relative price of the ethanol by-product and the ethanol price, the horizontal factor does not. As long as $r < 1$, the conversion coefficient for prices is smaller than that for quantities.

To illustrate the concepts related to the horizontal (quantity) link between corn and ethanol, we use the data from the United States Department of Agriculture (USDA) for marketing years 2001/02 to 2009/10 (Table 2).[24] All reported data relate to yellow corn. Therefore, the amount of domestic non-ethanol corn and corn for exports combined represent the quantity C_{NEY} in the first panel of Figure 1, not C_{NE}. Similarly, the observed amount of corn for ethanol production corresponds to the distance $C_{NEY}Q_C$; in order to compute the counterfactual

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

amount of corn that would be processed into ethanol in the absence of the by-product, the values in the fourth column of Table 2 need to be multiplied by $(1-\gamma) \approx 0.7$.

The sixth column lists empirical estimates for the corn-ethanol quantity coefficient, obtained by dividing the actual ethanol production by the amount of corn used for ethanol. The empirical ratio ranges between 2.65 and 2.81 and thus closely resembles the conversion factor of $\beta = 2.8$. This is in accord with the idea that the distance $C_{NEY}Q_C$ in Figure 1 represents the total amount of corn used for ethanol production; that is, including the recycled corn.

The last two columns of Table 2 present estimates of elasticities for the ethanol supply curve S_E[25] under two different assumptions about elasticities of the underlying corn supply and demand curves. The first scenario assumes elasticities for corn supply, domestic corn demand and export demand (0.4, -0.2 and -1, respectively) as reported in de Gorter and Just (2009b); the second scenario assumes values adopted from Cui at al. (2010) (0.23, -0.2 and -1.73). The ethanol supply appears to be becoming less elastic over time, largely because of an increasing share of ethanol corn in corn supply and feed/food demand, respectively.

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 and an ethanol production subsidy, respectively. Figures 4 to 7 then analyze the impact of a binding ethanol blend mandate alone; in combination with a tax credit; corn production subsidy; and ethanol production subsidy, respectively. In all figures, we assume a close economy for oil (gasoline); the demand for non-ethanol corn is the horizontal sum of domestic and export

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

demand for corn, inclusive of the by-product. We analyze an endogenous oil price in an extended model presented in the appendices. Finally, in numerical simulations we assume an endogenous oil price, international trade in oil and corn, as well as a fuel tax in the domestic economy – features omitted from the analytical model for tractability.

Corn Production Subsidy and Blender's Tax Credit

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. Owing to this, 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 (is linked to the oil price), the effect of the corn production subsidy is to expand ethanol production from Q_E to Q'_E. But why should ethanol producers produce more ethanol if they receive the same market price?

To answer this question, note that before the corn production subsidy, the quantity of corn for ethanol production is given by distance C_YQ_C, corresponding 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 and the assumption of perfect competition among ethanol producers.

Suppose for a moment that an ethanol producer does not change the level of production when the subsidy is introduced. That is, the demand for corn is still C_YQ_C. With the subsidy, however, the same quantity of corn can be purchased at a lower price denoted as P'_C (not shown); the market price of ethanol remains constant at P_E. Hence, under the corn production subsidy the corresponding profits for an ethanol producer 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 $P'_C < P_C$.

Positive value of expression (9) implies windfall profits. Therefore, new producers will enter the market and produce more ethanol, thus consuming more corn; alternatively, the incumbent producers may expand their production. Competition ensures that the producers bid up the price of corn back to P_C and more corn is processed for ethanol.

Because the corn market price in Figure 2 does not change with the corn production subsidy, so does not consumption of corn for feed/food use. This situation motivates the notion of the recycling effect because it is probably the only explanation how the corn and ethanol markets can be in equilibrium under the conditions above. The additional quantity of 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 by-product induced by the corn production subsidy.

In terms of market effects of the corn production subsidy, in the fuel market it does expand the supply of ethanol (curve S'_E), but the ethanol market price does not change (to the extent that the expanded ethanol production does not affect the world oil price; we relax this assumption in the appendices). Corn producers receive the market price of corn plus the corn production subsidy. Ethanol producers benefit from the subsidy by receiving the ethanol market price and, effectively, an equivalent of the subsidy in dollars per gasoline-equivalent gallon of ethanol. Note also that because the corn production subsidy expands ethanol production, more by-product is returned to the corn market which crowds out yellow corn from feed/food consumption; hence the consumption of yellow corn decreases to C'_Y.

Ethanol Production Subsidy and Blender's Tax Credit

Market effects of an ethanol production subsidy s_E are presented in Figure 3. The subsidy reduces the marginal cost of ethanol production – a vertical shift of S_E to S'_E in the second panel of Figure 3 – expanding it from Q_E to Q'_E. Ethanol producers receive a price that exceeds the ethanol market price by the full amount of the subsidy; that is, $P_E + s_E$. Corn producers benefit from the ethanol production subsidy because they expand production from Q_C to Q'_C. On the other hand, 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.[26]

The comparative static results for a model with an endogenous gasoline price and a binding tax credit are presented in Table 3 (see appendix 1 for details). The tax credit reduces the gasoline and fuel prices, while increases the ethanol and corn ones. This happens because the tax credit induces higher ethanol production, and hence also higher corn production. On the other hand, ethanol crowds out gasoline whose production goes down, thus the decrease in the gasoline price. As we show in appendix 1, in equilibrium the fuel price has to equal the gasoline price. Corn production subsidy has a negative effect on all prices. This is because it lowers the marginal cost of corn production, thereby expanding ethanol production as it becomes less costly. Finally, the ethanol production subsidy, by reducing the ethanol market price, lowers the marginal cost to fuel blenders, while expanding ethanol production because the producers receive the ethanol market price and the subsidy. The corn price increases because it is linked to the price received by ethanol producers.

[26] As the consumption of non-ethanol corn contracts, it is more likely that the technological constraint, if any, considered in footnote 16 will be binding.

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 does an ethanol production subsidy. This occurs even though the former increases and the latter reduces the ethanol market price. The reduction in the ethanol market price due to the ethanol production subsidy is more than offset by the subsidy itself, hence ethanol producers benefit.

Biofuel Blend Mandate

Rather than focusing on the economics of a biofuel blend mandate depicted in the second panel of Figure 4, we analyze the market effects of the mandate on the corn-fuel market equilibrium.[27] An exposition of the economics of a biofuel blend mandate is provided in de Gorter and Just (2009b). The purpose of Figure 4 is to show how consideration of the ethanol by-product, which is equivalent to assuming a flatter ethanol supply curve (S'_E in the first panel), changes the ethanol market price: the price is reduced relative to the counterfactual – from P_E to P'_E. The same is true of the corn market price. Compare this with a counterpart situation in Figure 1 where a blender's tax credit is the binding biofuel policy. In that situation, the flatness of the ethanol supply curve has no effect on ethanol and corn prices. Notice also that under the blend mandate alone, the ethanol market price coincides with the price received by ethanol producers. Even though the quantity of yellow corn is lower compared to when the by-product is

[27] In figure 4, D_F, S_F and P_F denote demand, supply and price of fuel (a blend of gasoline and ethanol); α denotes the percentage blend. The notation on the horizontal axes is self-explanatory.

not considered ($Q'_C < Q_C$), the final quantity of ethanol is higher, $Q'_E > Q_E$. This occurs because of the by-product's recycling effect.

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. Its incidence is to reduce the fuel price and increase the ethanol market price. This is shown in the second panel of Figure 5 where the marginal cost of the final fuel blend S_F shifts down by an amount of the tax credit adjusted for the share of ethanol in the fuel, αt_c. As a result, the pre-tax credit fuel price P_F drops to P'_F and fuel consumption increases. Corresponding to higher fuel consumption is higher ethanol production. Because the ethanol supply curve is unaffected by the introduction of the tax credit, more ethanol can be produced only at a higher market price of the biofuel, an increase from P_E to P'_E. The corn market price follows an increase in the ethanol market price, denoted by P'_C. However, this increase is likely to be small because demand for fuel is price inelastic and the ethanol supply curve is more elastic than assumed (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).

Binding Biofuel Blend Mandate and a Corn Production Subsidy

The effect of a corn production subsidy s_C on the corn supply curve and demand for non-ethanol yellow corn in the first panel of Figure 6 is identical to that depicted in figure 2. The corn production subsidy makes the ethanol supply curve shift to S'_E, which in turn lowers the marginal cost of the final fuel supply 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. Because in equilibrium quantities of fuel and ethanol are linked through a 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 is lower than prior to 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 second panel of Figure 6 poses a situation – similar, but not identical to that in Figure 2 – where ethanol producers receive a lower market price and yet supply more. This needs to be defended. Profits per bushel of corn to ethanol producers are

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

and after the corn production subsidy

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

Then,

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

Because a production subsidy always lowers the market price of a product (corn in our case), it must be the case that $P_C' - P_C < 0$. Assume for a moment that ethanol producers do not change production of ethanol when the corn production subsidy is provided. Then $P_E' = P_E$ and $\Delta\pi = -\left(1 - r\gamma\right)\left(P_C' - P_C\right) > 0$. Akin to the situation in Figure 2, windfall profits and competition among ethanol producers will result in higher ethanol production. But because the implicit demand of fuel blenders for ethanol αD_F has a negative slope, more ethanol will be blended only if the fuel price decreases. For that to happen, the price of ethanol must decrease.[28] Ethanol producers will expand their production and reduce ethanol price until zero profits are made, or in terms of equation (12)

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

A new equilibrium is established where the negative term in equation (13) is exactly offset by the positive term.

Binding Biofuel Blend Mandate and an Ethanol Production Subsidy

Ethanol production subsidy s_E lowers 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 lowers 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, fuel price decreases from P_F to P'_F, while fuel consumption increases from C_F to C'_F. In this respect, 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, ethanol price received by ethanol producers is equal to the market price of ethanol plus the production subsidy. 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 corn production subsidy is likely to be small because of inelastic demand for fuel and a relatively elastic ethanol supply curve.

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

The comparative statics results, presented in Table 4, for the binding blend mandate are largely 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. It is because with a binding mandate, all these policies implicitly subsidize fuel consumption which implies also more gasoline, hence the increase in its price. Moreover, an increase in the blend mandate always reduces the gasoline price (because the mandate is an implicit tax on gasoline (oil) consumption), whereas its impact on the market price of fuel, ethanol, or corn is ambiguous. While the ambiguous effect on the fuel price has been well documented (de Gorter and Just 2009b; Lapan and Moschini 2009), we are not aware of that on the ethanol price. Intuitively (although not completely technically correct), because the fuel price can either increase or decrease, so can the amount of fuel. But because the amount of ethanol is linked to the amount fuel through the blend mandate, its change can be either positive or negative. If the latter is the case, the ethanol price 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 when ethanol consumption is not mandated but 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 consumers do not demand a fuel *per se*, but rather miles the fuel produces. Therefore, assuming consumers have a choice between gasoline and ethanol, they will be willing to pay for one gallon of ethanol only a portion, 70 percent, of the price charged for one gallon of gasoline. We also assume consumers 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 also the logic behind equation (5).

Since equation (5) determines ethanol market price for any blender's tax credit, and because it assumes the tax credit is the only biofuel policy, by setting the tax credit to zero, we obtain a hypothetical ethanol market price P_E^* that would render consumers indifferent between ethanol and gasoline under no biofuel policy at all

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

Note that because $P_E^* < P_G^*$, ethanol production is very unlikely[29] to occur at this ethanol price for the intercept of the ethanol supply curve has historically been above the gasoline market price.

Because the hypothetical ethanol market price relates to no ethanol policy, and no ethanol production occurs, P_G^* denotes a gasoline price corresponding to the intersection of demand and supply curves for gasoline (or excess demand and supply curves under international trade). Note that the hypothetical ethanol market price (14) is immune to any biofuel policy. This is advantageous for comparison market effects across various biofuel policies. Notice also that owing to the absence of the tax credit, the hypothetical ethanol price can be comparatively low.

The concept of 'water' in a biofuel policy naturally flows from two prices already discussed: the intercept of ethanol supply curve (P_{NE}) and the hypothetical ethanol market price

[29] In the analysis to follow, we rule out this possibility.

(P_E^*). Intuitively, if P_{NE} is above P_E^*, then a part of the effect of a biofuel policy to increase the corn price will not be effective, just filling up the gap between P_{NE} and P_E^*. This is referred to as 'water'. This means, within the range of 'water', a biofuel policy has no effect on corn prices, costs taxpayers and benefits nobody.

Although de Gorter and Just (2008, 2009a) were first to recognize 'water' in a biofuel policy (tax credit) and the associated 'rectangular' deadweight costs, their definition of 'water' does not take into account the penalty due to the volumetric fuel tax.[30] They define 'water' w as the difference between the intercept of the ethanol supply curve P_{NE} and a prevailing gasoline (oil) price P_{Gb} (expressed in dollars per bushel) under a biofuel policy

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

But in reality, the tax is not negligible relative to the gasoline price, and its effect is therefore likely to change an estimate of 'water' (and thus rectangular deadweight costs) significantly.

To illustrate the concepts, we take the tax credit as an example. The same logic holds for the mandate, where one would consider the ethanol price premium due to the mandate instead of the tax credit. Assume no biofuel policy in Figure 1. Corresponding to this situation is an ethanol price P_E^* defined by equation (14).[31] Consider a (sufficiently large) tax credit t_c that increases the ethanol market price to P_E, defined by equation (5). Recalling that water is a range where a biofuel policy has no impact on the corn price, it is natural to define the water as the difference between the intercept of the ethanol supply curve P_{NE} and P_E^* (in dollars per bushel)

[30] In that respect, their 'water' is just a special case under a zero fuel tax.
[31] Price of gasoline is depicted below the intercept of the ethanol supply curve only in Figure 1. In other figures, we do not depict 'water'; hence, price of gasoline is above P_{NE}. This does not affect our graphical analyses in other figures.

$$w = P_{NE} - \frac{\lambda\beta}{1-r\gamma}\left(P_G - \left(\frac{1}{\lambda}-1\right)t - c_0\right) \tag{16}$$

The 'water' is then equal to the distance *fc* in the first panel of Figure 1. But this distance is always greater than the distance *fd*, corresponding to the 'water' as originally defined in de Gorter and Just (2008, 2009a). The reason is a penalty to fuel blenders due to the volumetric fuel tax, distance *dc*; hence the underestimate of 'water' in de Gorter and Just (2009a). Clearly, if the fuel tax is zero, then the two definitions are identical.

We measure the *price premium* of a biofuel policy in the corn market by taking the difference between a corn market price and the hypothetical ethanol price (in dollars per bushel).[32] Since the hypothetical ethanol price is policy-invariant, the price premium can change only if the corn price changes. One would obtain identical results (after adjusting for units), if the premium were measured in the fuel market by the difference between the ethanol market price and the hypothetical ethanol price. There is one exception, however: when a biofuel policy mix includes the ethanol production subsidy.

This is because the ethanol production subsidy drives a wedge between the ethanol market price and the price received by ethanol producers; the latter determines, via equation (2), the corn market price. Therefore, with an ethanol production subsidy, there are two unique effects (unlike for other policies analyzed): the ethanol market price decreases (but perhaps only marginally), while the corn price increases.

Explicitly embedded in equation (16) is the fact that the fuel market is distorted by the volumetric fuel tax: consumers are willing to pay a price of fuel (inclusive of the tax) by the

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[32] We measure the premium in the corn market for convenience; it shows better how a biofuel policy affects the corn market prices.

mileage the fuel produces, while blenders are taxed by the volume. To attain a distortion-free economy, a tax credit equal to the penalty due to the volumetric fuel tax is required[33]

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

It could therefore be argued that the 'water' should be calculated with respect to a distortion-free price of ethanol – such, that equals the price of gasoline when expressed in GEGs. But this is just a flip side of the same coin because one part of water relates to the tax credit $\hat{t}_c$ necessary to keep a distortion-free fuel market, while the other part is necessary to increase the corn price to a point where ethanol production could start, that is, to P_{NE}. In total, the two parts of 'water' give the total 'wate'r identified earlier – equal to the distance *fc* in the first panel of Figure 1.

The 'rectangular' deadweight costs due to 'water' are equal to the product of the amount of yellow corn used in ethanol production and the associated per unit 'water' in \$/bu; in the first panel of Figure 1, these costs correspond to the shaded area *acfh*. However, de Gorter and Just (2009a) in their graphical analysis relate them to the horizontal distance between S_C and D_{NE} (at a corn market price), omitting to recognize that with ethanol production, D_{NE} represents the total demand for non-ethanol corn equivalent which includes the ethanol by-product. Considering their definition of water, they estimate the rectangular deadweight costs to be the area *edfg*. For a given oil price, the area *acfh* is, however, unequivocally larger than *edfg*, with the difference heavily depending on (*i*) elasticity of the corn supply curve and domestic and export demand for non-ethanol corn and (*ii*) the level of the fuel tax.

The foregoing analysis has assumed consumers can buy a fuel with any share of ethanol as long as the price per mile traveled is equalized between ethanol and gasoline. This assumption is mostly not met in reality, however, because currently most gas stations offer premixed blends

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

of fuel containing 10, 15, or 85 percent of ethanol. Blenders, in adding ethanol to gasoline, are essentially "watering down the scotch". This situation represents a *de facto* mandate, because consumers 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.

A third option occurs when there is no biofuel policy, but nevertheless ethanol is consumed. This occurred after the ban of MTBE, a low cost alternative to ethanol, in 2006. This is also a de facto mandate because ethanol, as an oxygenator and octane enhancer, is consumed in a certain proportion to gasoline. This proportion is however, typically lower compared to the regular blend mandate. It could therefore be argued that ethanol market price under this scenario should be the no-policy counterfactual, and not the hypothetical price given by equation (14). In this case, our definition represents an upper bound on water. But this does not automatically mean the ethanol would come from U.S. sources as sugar-cane ethanol in Brazil has been much more cost-competitive over the years, even taking into account transportation costs to the United States. This means the U.S. ethanol import tariffs of 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, we calibrate a model using the data and parameters detailed in appendix 4.[34] We assume supply and demand curves in all markets exhibit

[34] All models are calibrated to the observed market prices and quantities, assuming that the blend mandate determines the ethanol market price. This assumption is likely to be violated in the resent period, however, because since the end of 2010 the ethanol market price seems to be determined outside of the United States; hence, the U.S.

constant price elasticities. The U.S. corn production supplies domestic demand for yellow corn, export demand, as well as the demand for corn to be used in ethanol production. The United States is an importer of fossil fuel (gasoline) and is assumed to consume the entire production of ethanol; thus, the rest of the world consumes only gasoline. We model various combinations of four biofuel policies: a blend mandate, blender's tax credit, ethanol production subsidy and corn production subsidy.

Table 5 provides an overview of a relative position 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^*, that would prevail in the fuel market if no biofuel policies were in place. For convenience, ethanol prices are expressed also in dollars per gallon, that is, not adjusted for mileage. The theoretical gasoline prices are always higher than the observed ones; the difference ranges between one and two 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 current 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.[35] However, it should come as no surprise that even a small change in gasoline price can result in sizable monetary changes because of a large amount of gasoline affected.

The hypothetical ethanol market price is significantly lower compared to the observed ethanol price and attains only around 70 percent of it over the analyzed period (in 2009 even less, 62 percent). The hypothetical price is low relative to the observed one because of the missing

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mandate is dormant. This however, does not affect our major conclusions, because most of our results are based on observed data.

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

blender's tax credit. Note that the hypothetical ethanol price is significantly below the hypothetical gasoline price P_G^* because of the existing fuel tax; the difference is equal to $0.43 \times$ *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 (projected price), that is, years that saw spikes in food commodity prices. The intercept of the ethanol supply curve corresponds to the intersection of supply curve and the total demand for non-ethanol corn. It varies over time, reaching peaks in 2008 ($3.80/bu) and 2011 ($4.19). Although the peaks coincide with the years when commodity prices spiked, it does not automatically imply that the observed commodity price spikes were only due to shifts (shocks) in the corn demand or supply. It is because when the tax credit determines the ethanol price (and the oil supply is perfectly elastic), then any shock in the corn market has zero effect on the corn price (unless the change in ethanol production affects the oil price). The third raw of Table 6 presents the hypothetical ethanol market price expressed in dollars per bushel (a counterpart to Table 5).

The ethanol policy price premium in Table 6 is obtained by subtracting the values in the third raw from those in the first raw. [36] There are at least four reasons why the observed ethanol price premium is so high. First, the actual blend mandate is binding. Second, consumers have a very limited choice to purchase fuel according to mileage because there are few E-85/E-15 outlets; this imposes a *de facto* mandate, in which case the actual blend is greater than the mandated one. Third, MTBE ban and Clear Air Act, for example, also constitute a *de facto* mandate (and an import tariff 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 this price

[36] 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 as a result, the price premium would increase.

exceeds a price the U.S. biofuel policies would generate, then a high price premium (even higher than with the mandate alone) occurs as a result (de Gorter et al. 2011).

Finally, in the last row we report a change in the corn market price attributable 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).

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 in some year a corn price is below P_{NE} (because of too high water), then no ethanol production would have occurred in that year. This is the case for 2008 and 2009, as the first line of Table 7 documents. For example, because the per-bushel-of-corn equivalent of the 2008 58¢/gal blender's tax credit is $2.20/bu and water associated with the tax credit alone is $2.60/bu (not reported), the net effect of the introduction of the tax credit on corn prices is negative 40¢/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 $0.69/bu – $1.48/bu more than does the tax credit (denoted as mandate differential in Table 7). But if one adds the ethanol production subsidies, this differential declines to $0.18/bu – $0.98/bu; it falls even more, $0.13/bu – $0.92/bu, if both corn and ethanol production subsidies are added to each of the tax credit or mandate. Note that the final row in Table 7 shows corn prices increase by $0.93/bu – $1.88/bu due to corn subsidies and the three ethanol policies combined (as is the actual case), which corresponds to a 26 – 45 percent increase in the corn price.

Table 8 presents estimates of rectangular deadweight costs for the observed baseline (all four policies combined) in the period 2008 – 2011. For example, the values in the first row suggest that the rectangular deadweight costs totaled 32.5 billion dollars (in nominal terms) over the four years analyzed.[37] The deadweight loss due to the penalty takes a significant share in the total rectangular deadweight costs – between one fifth and one third, depending on the year. This is one source of a significant underestimate of rectangular deadweight costs as calculated in de Gorter and Just (2009a). The other source is that de Gorter and Just, by omitting the recycling effect, do not take into account all yellow corn that is an input to ethanol production. Overall, our estimates of rectangular deadweight cost are higher, relative to de Gorter and Just's, by 80 to 120 percent, depending on the year.

Conclusions

This paper has advanced 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 and corn). More specifically, 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 by-product, we conclude that the ethanol supply curve is more elastic than thought, because more yellow corn is 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 purchase of gasoline and ethanol if there were no biofuel policies (and consumers demand 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, which has been used in the previous literature. Thus, our results show

[37] Note that in 2009, rectangular deadweight costs about exactly offset the social welfare gains of an optimal blender's tax credit or mandate reported in Cui et al. (2010).

that the rectangular deadweight costs associated with water were significantly 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, which we define as the difference between the observed corn price and a hypothetical ethanol price (in dollars per bushel), is very high; for example in 2008 it is estimated to be $3.58/bu, representing 56 percent of the ethanol market price. On the other hand, the impact of the price premium due to biofuel policies on corn market prices, although still significant, is tempered by existing 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. This price is affected, among other things, also by U.S. biofuel policies aimed at non-corn ethanol biofuels (e.g., biodiesel or cellulosic ethanol) and by biofuel policies in the rest of the world. The former channel occurs through competition for agricultural land which increases the marginal cost to corn producers and therefore shifts the corn supply curve up, thus increasing the non-ethanol corn price. The latter channel is reflected in the demand for the U.S. yellow corn exports. Because biofuel policies in the rest of the world make the export demand for yellow corn facing the United States increase, the non-ethanol corn price rises. The implication is that the impact of the U.S. biofuel policies on corn prices would have been higher, if there had been no biofuel policies in the rest of the world.

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Figure 1. Equilibrium in the corn and ethanol markets with a binding blender's tax credit

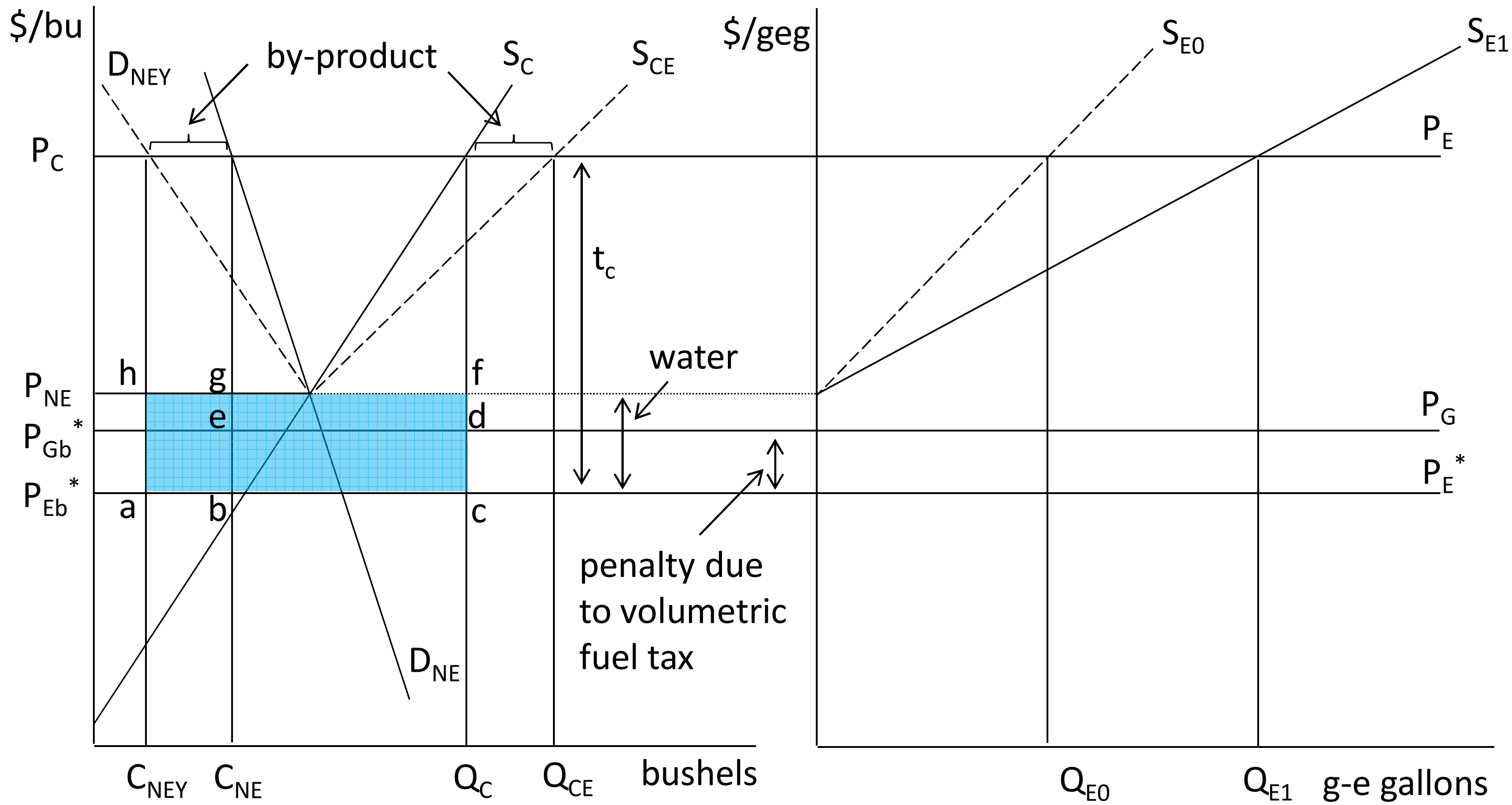

Figure 2. Equilibrium in the corn and ethanol markets with a binding blender’s tax credit and a corn production subsidy

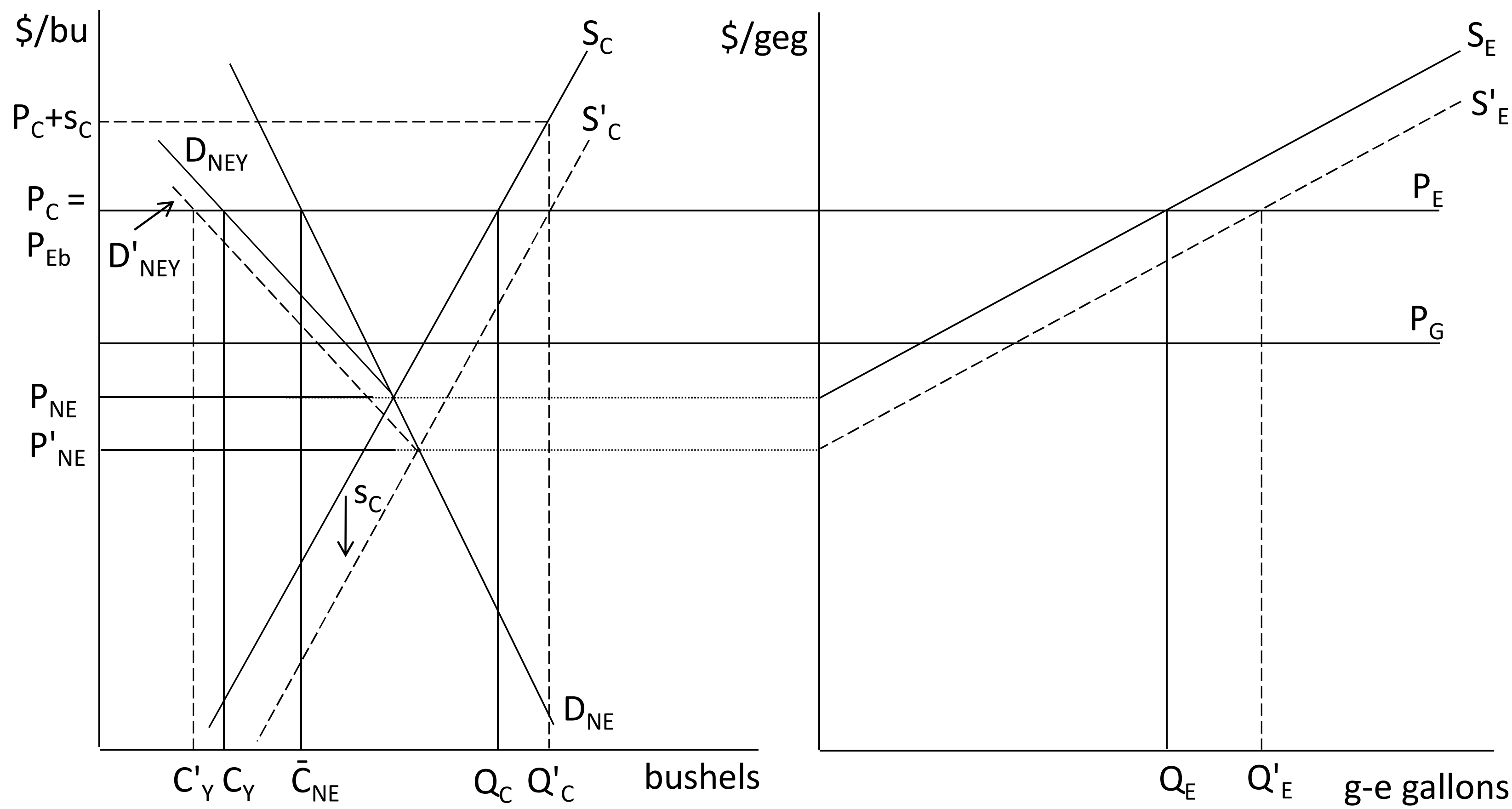

Figure 3. Equilibrium in the corn and ethanol markets with a binding blender's tax credit and an ethanol production subsidy

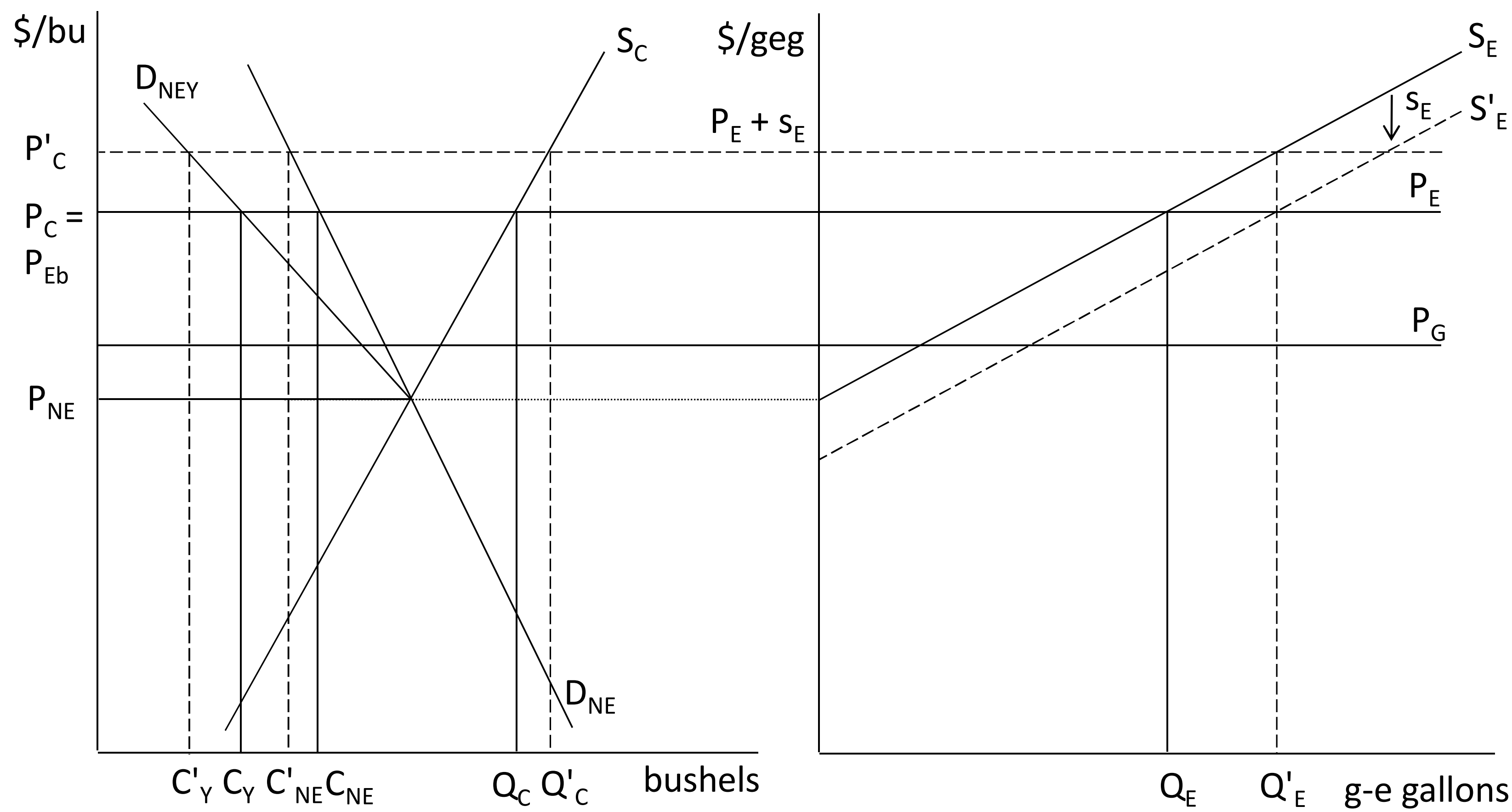

Figure 4. Equilibrium in the corn and ethanol markets with a binding blend mandate

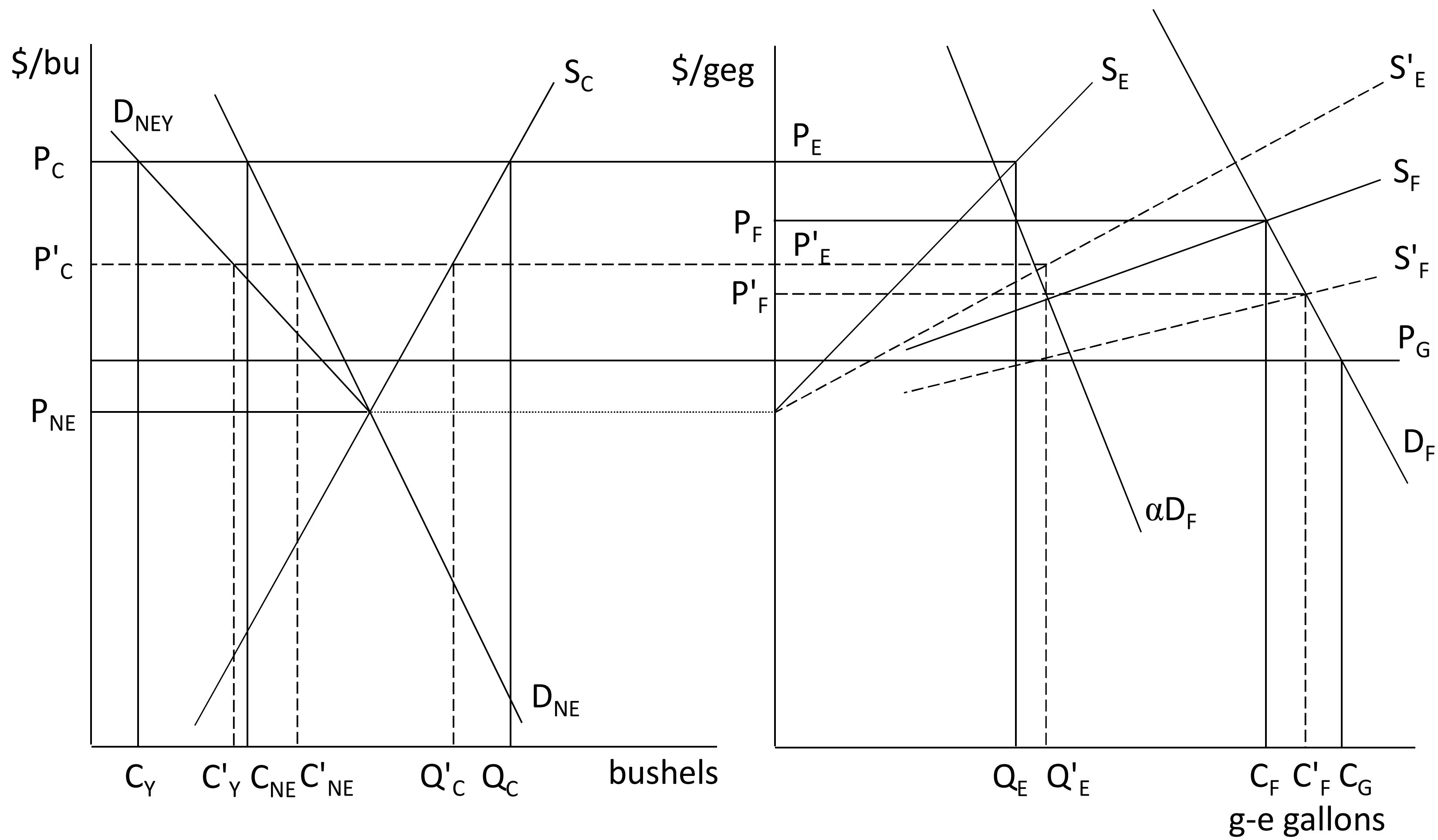

Figure 5. Equilibrium in the corn and ethanol markets with a binding blend mandate and a tax credit

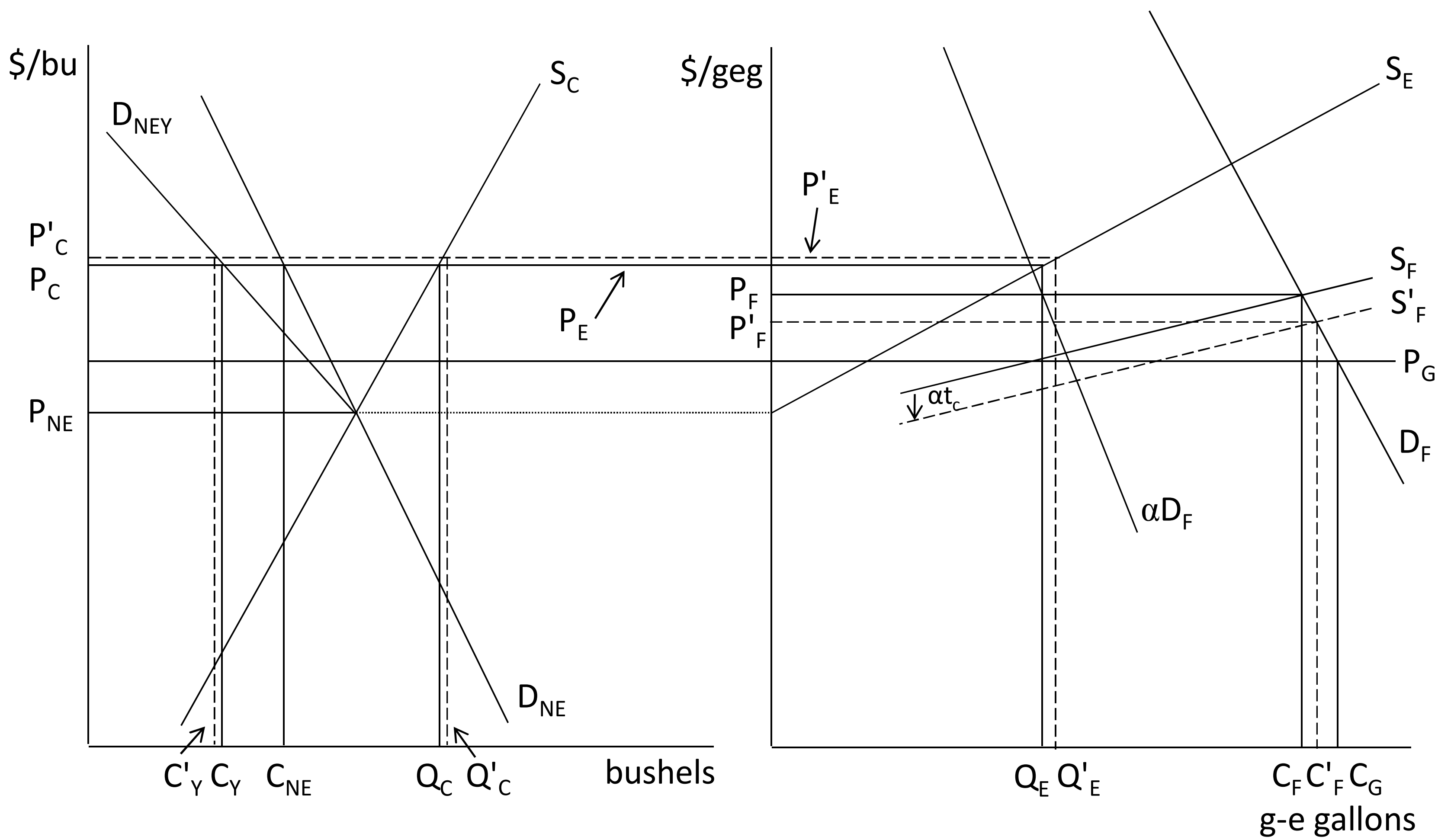

Figure 6. Equilibrium in the corn and ethanol markets with a binding blend mandate and a corn production subsidy

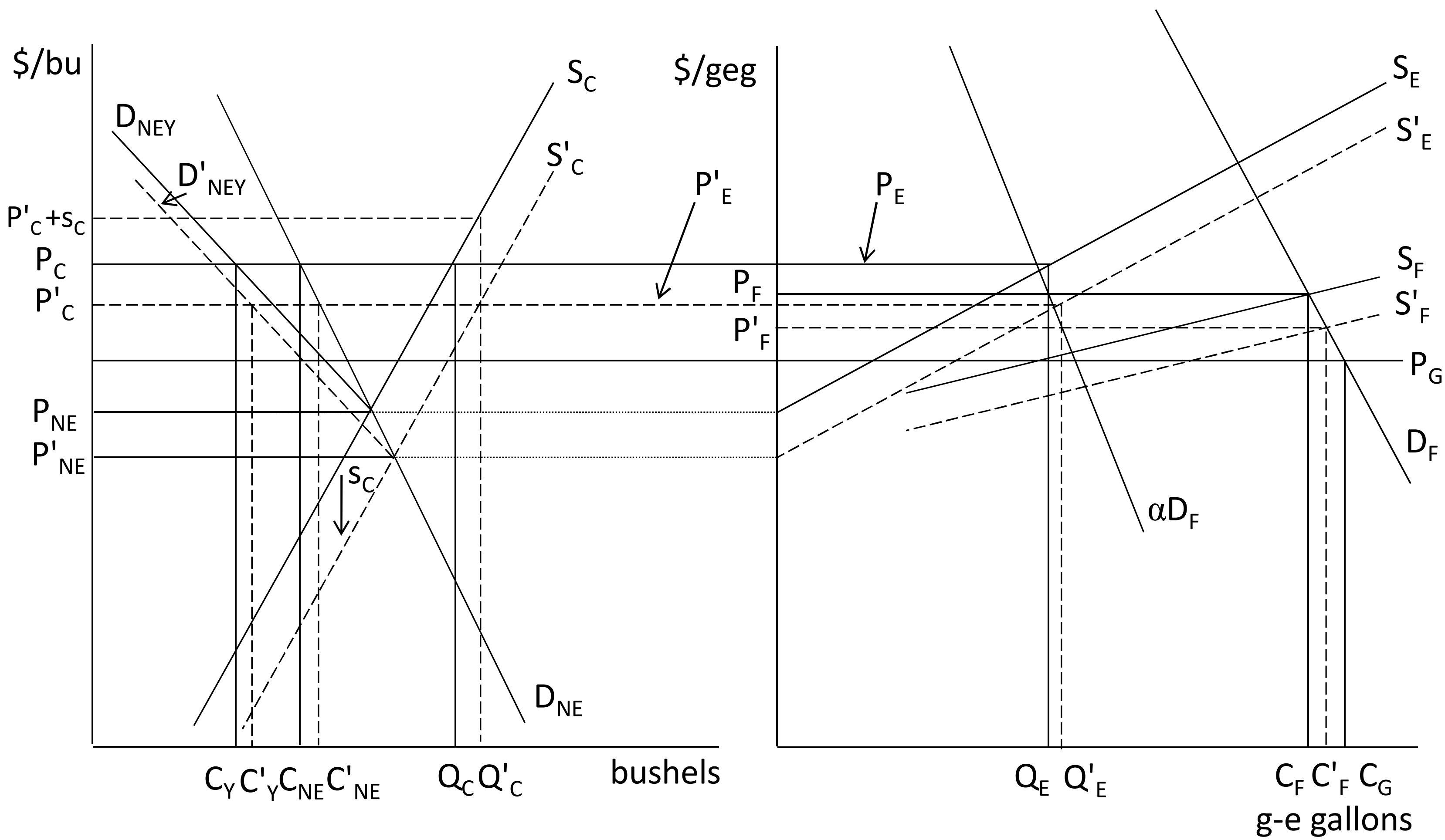

Figure 7. Equilibrium in the corn and ethanol markets with a binding blend mandate and an ethanol production subsidy

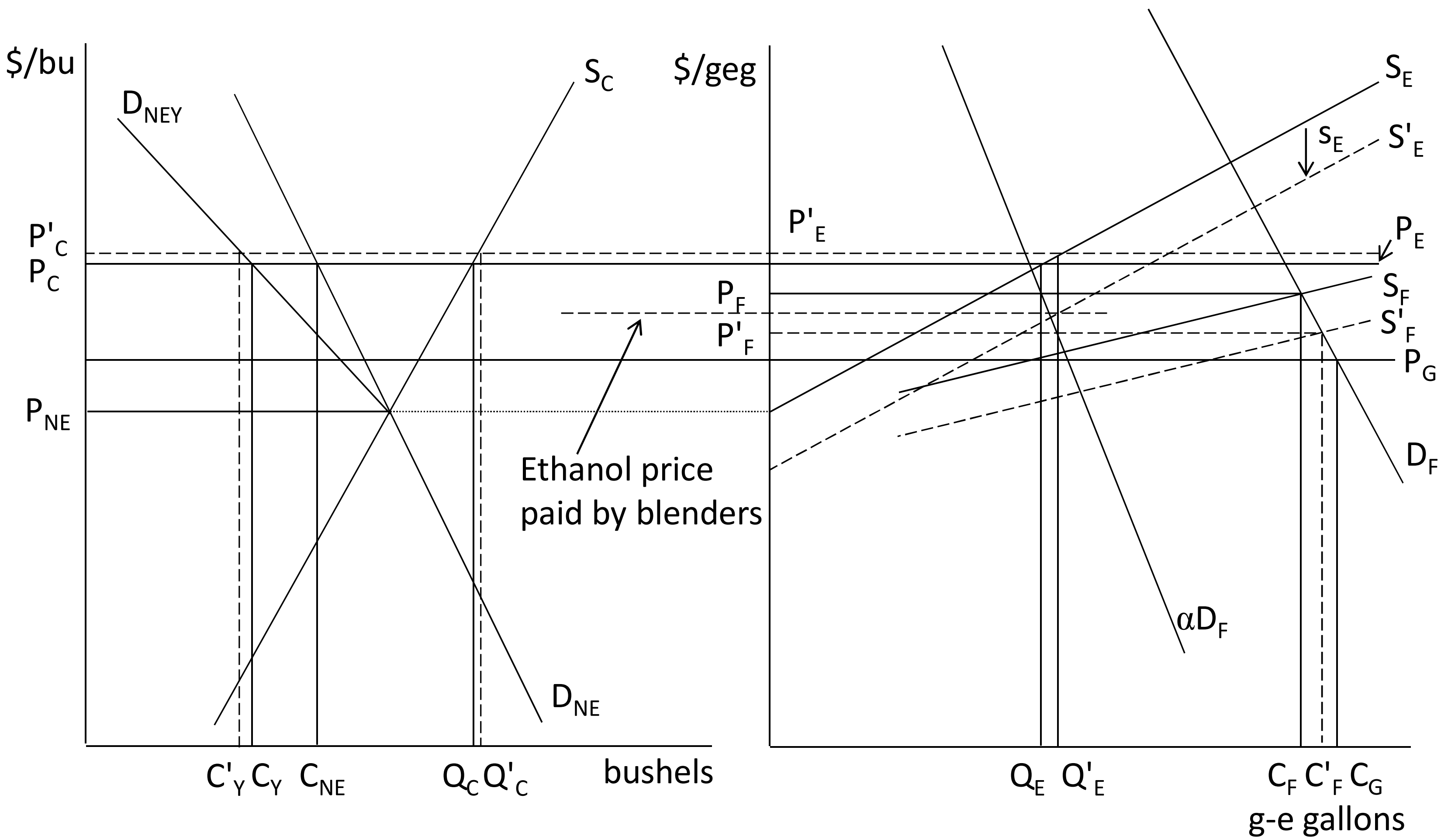

Table 1. Comparison of Observed and Predicted Ethnol-corn Price Conversion Factors

Year	Profit per gal. (π)	$P_C/(P_E-c_0)$	$P_C/(P_E-c_0-\pi)$	$\beta/(1-r\gamma)$
	(1)	(2)	(3)	(4)
2005*	0.48	2.62	4.32	4.27
2006	1.21	1.43	4.15	3.96
2007	0.32	2.94	3.91	3.78
2008	0.07	3.61	3.79	3.80
2009	0.11	3.53	3.91	3.80
2010	0.08	3.59	3.86	3.77
2011**	0.00	3.69	3.71	3.69

Source: caluclated

Note: * May-December; ** January-June.

The values above are simple averages for a given year. They are not adjusted for mileage of ethanol. To obtain values expressed per gasoline-equivalent gallon of ethanol, the values in column (1) need to divided and those in columns (2) to (4) multiplied by 0.7.

Table 2. Estimated Elasticity of the Ethanol Supply S_E

	Million Bushels				Million gallons			η_{SC}=0.40, η_{DD}=-0.20, η_{DX}=-1.00 *	η_{SC}=0.23, η_{DD}=-0.20, η_{DX}=-1.73 †
	Supply	Domestic non-ethanol use	Exports	Ethanol Q_{CE}	Ethanol prod. Q_E	Q_E/Q_{CE}	$P_E/(P_E-c_0)$	Elasticity of S_E ‡	Elasticity of S_E
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
2001-02	9820	7201.2	1905	713.8	1936.3	2.71	2.10	21.39	20.63
2002-03	9490	6907	1588	996	2634.5	2.65	3.80	25.81	24.14
2003-04	10232	7164	1900	1168	3227.8	2.76	2.99	19.04	18.18
2004-05	10662	7521	1818	1323	3687.5	2.79	2.08	11.96	11.22
2005-06	11270	7533	2134	1603	4500.2	2.81	1.48	7.50	7.19
2006-07	11210	6966	2125	2119	5883.0	2.78	1.61	6.07	5.82
2007-08	12738	7251	2437	3049	8367.2	2.74	1.60	4.72	4.53
2008-09	12057	6498	1849	3709	10304.7	2.78	1.77	3.79	3.47
2009-10	13065	6495	1980	4591	12669.8	2.76	1.71	3.17	2.34

Source: USDA WASDE reports; EIA - Table 10.3 Fuel Ethanol Overview; CARD - Historical Ethanol Operating Margins; calculated

Note: * de Gorter and Just (2009b).

† Cui et al (2010).

‡ Formula for elasticity of the ethanol supply curve is in appendix 3.

Table 5. Gasoline and Ethanol Prices

	2008	2009	2010	2011§
Observed gasoline price P_G ($/gal)	2.57	1.76	2.17	2.95
Hypothetical gasoline price (no ethanol) P_G^* ($/gal)	2.60	1.78	2.21	3.00
Observed ethanol price P_E ($/gal)	2.47	1.79	1.93	2.71
Hypothetical ethanol price (no biofuel policy) P_E^* ($/gal)	1.67	1.10	1.40	1.95
Observed ethanol price P_E ($/GEG)	3.53	2.56	2.76	3.86
Hypothetical ethanol price (no biofuel policy) P_E^* ($/GEG)	2.39	1.58	2.00	2.79
Hypothetical ethanol price as % of observed ethanol price	68	62	72	72
Hypothetical ethanol price as % of hypothetical gasoline price	92	88	91	93

Source: caluclated

Note: § - projected values

Table 6. Ethanol Price Premium due to All four Policies ($/bu)†

	2008	2009	2010	2011§
Observed corn price P_C	4.78	3.75	3.83	6.07
Non-ethanol corn price P_{NE}	3.80	2.82	2.77	4.19
Hypothetical ('no-policy') ethanol price P_E^*	1.20	0.60	1.28	2.75
Ethanol price premium = $P_C - P_E^*$	3.58	3.15	2.55	3.32
Net change in corn price $\Delta P_C = P_C - P_{NE}$	0.98	0.93	1.06	1.88

Source: caluclated

Note: § - projected values

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

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	-0.40	-10.6	-0.25	-9.0	0.42	15.2	0.45	10.6
Mandate	1.04	27.5	0.98	34.8	1.11	39.9	1.93	46.1
Mandate differential	**1.45**	**38.0**	**1.24**	**43.8**	**0.69**	**24.7**	**1.48**	**35.4**
Tax credit & ethanol production subsidy	0.14	3.6	0.28	9.8	0.93	33.6	0.95	22.7
Mandate & ethanol production subsidy	1.05	27.5	0.99	34.9	1.11	40.0	1.93	46.1
Mandate differential	**0.91**	**23.9**	**0.71**	**25.1**	**0.18**	**6.4**	**0.98**	**23.4**
Tax credit & corn production subsidy	-0.40	-10.6	-0.25	-9.0	0.42	15.1	0.44	10.6
Mandate & corn production subsidy	0.97	25.6	0.92	32.5	1.05	38.0	1.87	44.6
Mandate differential	**1.38**	**36.2**	**1.17**	**41.5**	**0.64**	**22.9**	**1.43**	**34.1**
Tax credit & ethanol production subsidy & corn production subsidy	0.13	3.5	0.27	9.7	0.93	33.5	0.95	22.6
Mandate & ethanol production subsidy & corn production subsidy	0.97	25.6	0.92	32.6	1.06	38.1	1.87	44.7
Mandate differential	**0.84**	**22.1**	**0.65**	**22.8**	**0.13**	**4.6**	**0.92**	**22.1**
Mandate & tax credit & ethanol production subsidy & corn production subsidy	0.98	25.7	0.93	32.8	1.06	38.2	1.88	44.8

Source: calculated
Note: * projected values.
The discrepancies are due to rounding errors.

Table 8. Estimates of Rectangular Deadweight Costs for the Observed Baseline (all four policies)

	2008	2009	2010	2011*
Rectangular DWC (bil. $)	8.84	8.86	7.56	7.27
% of DWC due to penalty	21.0	23.9	34.7	37.6
% of rectangular DWC in value of corn production	14.4	18.3	14.3	10.1
DWC of de Gorter & Just (bil. $)	4.86	4.70	3.43	3.59
Difference (%)	81.8	88.7	120.2	102.3

Source: calculated
Note: * projected values
DWC - Deadweight costs
The four policies are: blender's tax credit, blend mandate, ethanol production subsidy, corn production subsidy.

Appendix 1. Model with an endogenous gasoline price and a binding tax credit

For analytical tractability, we present the model for a closed economy, assuming a zero fuel tax. All quantities are expressed in gasoline-equivalent gallons (GEGs). Ethanol and gasoline are assumed to be perfect substitutes, and consumers can choose which fuel to purchase. They value the fuel for mileages 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 ethanol market price P_E less the blender's tax credit t_c

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

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 a number of gallons of ethanol produced from one bushel of corn; r denotes the relative price of the ethanol by-product (DDGS) and corn; and γ denotes the share of corn that returns back to the market as the by-product.

Equilibrium in 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

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

where S_C denotes corn supply, D_{NE} is non-ethanol corn demand and s_C denotes a corn production subsidy.

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

$$\begin{aligned}
\frac{dP_F}{dt_c} = \frac{dP_G}{dt_c} &= -\frac{\frac{\lambda\beta}{1-\gamma}\frac{\lambda\beta}{1-r\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]}{S_G'-D_F'+\frac{\lambda\beta}{1-\gamma}\frac{\lambda\beta}{1-r\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]} < 0, > -1 \\
\frac{dP_E}{dt_c} &= \frac{S_G'-D_F'}{S_G'-D_F'+\frac{\lambda\beta}{1-\gamma}\frac{\lambda\beta}{1-r\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]} > 0, < 1 \\
\frac{dP_C}{dt_c} &= \frac{\frac{\lambda\beta}{1-r\gamma}(S_G'-D_F')}{S_G'-D_F'+\frac{\lambda\beta}{1-\gamma}\frac{\lambda\beta}{1-r\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]} > 0
\end{aligned} \tag{A1.5}$$

$$\begin{aligned}
\frac{dP_F}{ds_E} = \frac{dP_G}{ds_E} = \frac{dP_E}{ds_E} &= -\frac{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]}{S_G'-D_F'+\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]} < 0, > -1 \\
\frac{dP_C}{ds_E} &= \frac{\frac{\lambda\beta}{1-r\gamma}(S_G'-D_F')}{S_G'-D_F'+\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]} > 0
\end{aligned} \tag{A1.6}$$

$$\begin{aligned}
\frac{dP_F}{ds_C} = \frac{dP_G}{ds_C} = \frac{dP_E}{ds_C} &= -\frac{\frac{\lambda\beta}{1-\gamma}S_C'(P_C+s_C)}{S_G'-D_F'+\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]} < 0 \\
\frac{dP_C}{ds_C} &= -\frac{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}S_C'(P_C+s_C)}{S_G'-D_F'+\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]} < 0
\end{aligned} \tag{A1.7}$$

The set of derivatives (A1.5) reveals that if the tax credit is the binding biofuel policy, then its increase reduces gasoline (and fuel) price, 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, while the market price of corn rises (derivatives (A1.6)). The last set of derivatives (A1.7) shows that prices of fuel, gasoline and ethanol decrease by the same amount with an increase in the corn production subsidy; unlike the ethanol production subsidy, the corn market price decreases. 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

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

This means the probability that a corn production subsidy has a higher 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 more inelastic. The same holds for comparison of corn production subsidy and tax credit.

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

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

However, 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

This model considers all four policies; that is, a blend mandate, tax credit, ethanol production subsidy and corn production subsidy. The blend mandate is assumed to be binding (determines the ethanol market price). The first three equations are the same as in Appendix 1, hence need no explanation:

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

(A2.1)

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

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

With a blend mandate α, 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:

$$
\begin{aligned}
\frac{dP_F}{d\alpha} &= \frac{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(\left(P_E-t_c-P_G\right)S_G'-\left(1-\alpha\right)D_F\right)+\alpha S_G' D_F}{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2 D_F'\right)-\alpha^2 S_G' D_F'} \\
\frac{dP_G}{d\alpha} &= \frac{\frac{\lambda\beta}{1-\gamma}\frac{\lambda\beta}{1-r\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(\left(1-\alpha\right)\left(P_E-t_c-P_G\right)D_F'-D_F\right)+\alpha D_F D_F'}{\frac{\lambda\beta}{1-\gamma}\frac{\lambda\beta}{1-r\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2 D_F'\right)-\alpha^2 S_G' D_F'} < 0 \\
\frac{dP_E}{d\alpha} &= \frac{\left(S_G'-\left(1-\alpha\right)D_F'\right)D_F+\alpha\left(P_E-t_c-P_G\right)S_G' D_F'}{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2 D_F'\right)-\alpha^2 S_G' D_F'} \\
\frac{dP_C}{d\alpha} &= \frac{\frac{\lambda\beta}{1-r\gamma}\left(\left(S_G'-\left(1-\alpha\right)D_F'\right)D_F+\alpha\left(P_E-t_c-P_G\right)S_G' D_F'\right)}{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2 D_F'\right)-\alpha^2 S_G' D_F'}
\end{aligned}
\tag{A2.6}
$$

$$
\begin{aligned}
\frac{dP_F}{dt_c} &= -\frac{\alpha\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]S_G'}{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2 D_F'\right)-\alpha^2 S_G' D_F'} < 0 \\
\frac{dP_G}{dt_c} &= -\frac{\alpha\left(1-\alpha\right)\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]D_F'}{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2 D_F'\right)-\alpha^2 S_G' D_F'} > 0 \\
\frac{dP_E}{dt_c} &= -\frac{\alpha^2 S_G' D_F'}{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2 D_F'\right)-\alpha^2 S_G' D_F'} > 0, < 1 \\
\frac{dP_C}{dt_c} &= -\frac{\alpha^2\frac{\lambda\beta}{1-r\gamma}S_G' D_F'}{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'\left(P_C+s_C\right)-D_{NE}'\right]\left(S_G'-\left(1-\alpha\right)^2 D_F'\right)-\alpha^2 S_G' D_F'} > 0
\end{aligned}
\tag{A2.7}
$$

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

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

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

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

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

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

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

$$\frac{dP_C}{ds_C} = -\frac{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma} S_C'(P_C+s_C)\left(S_G'-(1-\alpha)^2 D_F'\right)}{\frac{\lambda\beta}{1-r\gamma}\frac{\lambda\beta}{1-\gamma}\left[S_C'(P_C+s_C)-D_{NE}'\right]\left(S_G'-(1-\alpha)^2 D_F'\right)-\alpha^2 S_G' D_F'} < 0 \tag{A2.9}$$

Appendix 3. Elasticity of the ethanol supply curve

Following figure 1, the ethanol supply can be written as:

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

where the right-hand side denotes by how much – at a given corn price – the domestic corn supply S_C exceeds the domestic non-ethanol demand D_D and foreign export demand D_X.

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

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

Likewise, from (A2.1) we have:

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

which, if substituted into (A3.2), produces:

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

(A3.4)

Manipulating equation (A3.4), we arrive at:

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

which converted into elasticities and rearranged further results in:

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

where □$_{SE}$, □$_{SC}$, □$_{DD}$ and □$_{DX}$ denote elasticity of ethanol supply, corn supply, domestic non-ethanol corn demand and export corn demand, respectively.

Finally, reapplying 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 amount of corn 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 an underestimate of its true value.

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	calculated
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 by-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	(-0.40) Drabik, de Gorter and Just (2010)
U.S. gasoline supply elasticity	(0.20) de Gorter and Just (2009b)
Foreign gasoline supply elasticity	(0.71) de Gorter and Just (2009b)
Elasticity of yellow corn supply	(0.23) Cui et al. (2010)
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	(-1.74) Cui et al. (2010)

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