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REGULAR ARTICLE

EMISSIONS FROM INDIRECT LAND USE CHANGE: DO THEY MATTER WITH FUEL MARKET LEAKAGES?

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ABSTRACT

Indirect land use change, an agricultural market leakage, has been a major controversy over the Environmental Protection Agency's (EPA) requirement for corn-ethanol to reduce greenhouse gas (GHG) emissions by 20 percent relative to gasoline it is assumed to replace. This paper shows that corn-ethanol policies generate far greater carbon leakage in the fuel market itself. Hence, corn-ethanol does not meet EPA's threshold, regardless of ethanol policy and whether one includes emissions from land use change.

Keywords: biofuels, ethanol, carbon leakage, emissions savings, tax credit, mandate
JEL: Q27, Q41, Q42, Q54

INTRODUCTION

The issue of carbon leakage – where greenhouse gas (GHG) emissions reductions by an environmental policy are partially or more than offset because of market effects – is often raised as an issue that will undermine environmental policies. Leakage has been extensively studied in the cases of cap and trade policies (see **Wooders and Cosbey 2009** for a survey), reduced deforestation and land degradation - REDD (e.g., **Murray 2008**) and indirect land use change generated from biofuels policies (e.g., **Searchinger et al. 2008**; **Al-Riffai, et al. 2010** provide one of many surveys on indirect land use change).

While emissions from land use change due to biofuel policies has attracted a significant amount of research, the same is not true for leakage in the fuel market itself – the focus of this paper – where the addition of biofuels causes a reduction in world oil (gasoline) market prices (**Drabik 2011; Hochman et al. 2011**).[1,2] To our knowledge, **de Gorter and Just (2009a)** were the first to point to this effect (calling it the "indirect output use effect"), but they only discuss the 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 the extensive and intensive margin changes in land use in the United States induced by biofuel policies and the implications of these policies for GHG emissions. Although they also provide estimates of leakage in the fuel market, they model the biofuel mandate differently. Namely, they assume consumers enjoy a choice between ethanol and gasoline even when the use of the former 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 (i.e., blend of ethanol and gasoline) is a weighted average of the ethanol and gasoline price (in energy equivalents), where the weights are represented by the share of ethanol and gasoline.

Rajagopal et al. (2011) empirically estimate fuel market leakage related to the U.S. ethanol blend mandate and find that the mandate combined with a blender's tax credit result in a reduction in global carbon emissions.[3] More recently, however, **Rajagopal and Plevin (2013)** showed that **Rajagopal et al. (2011)**'s results are likely to occur with a low probability (five percent or less). This is consistent with our results as we find that the corn-ethanol is associated with an increase in carbon emissions.[4,5] **Rajagopal (2013)** provides a survey of

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[1] In other words, we seek to quantify the market changes in the fuel market resulting from the introduction of biofuels via various biofuel policies. This means, production of biofuels is the only shock to the fuel market we analyze; therefore, we do not investigate how much would world oil consumption change, for example, due to a shock in the oil price.

[2] Assuming the crude oil price is endogenous.

[3] For ease of reference, under the term "carbon emissions" in the paper we mean carbon-equivalent greenhouse gas emissions at combustion.

[4] 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. It is 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

recent studies analyzing the fuel market leakage due to biofuel policies.

In 2007, legislation was introduced in the United States that requires one gasoline energy-equivalent gallon of ethanol to reduce GHG emissions by at least 20 percent relative to a gallon of gasoline that ethanol is assumed to replace. The 20 percent figure is the estimate based on "life-cycle accounting" (LCA), a "well to wheel" measure of GHGs emissions in the production of gasoline, and a "field to fuel tank" measure for ethanol production (**Farrell et al. 2006**).[6] If this requirement is not met, corn ethanol cannot be counted towards the mandate.

With the recent concern over global climate change in the United States, the corn-ethanol lobby quickly seized upon the benefits of ethanol in reducing GHG emissions. But this strategy back-fired because LCA is inherently flawed, as highlighted by **Searchinger et al. (2008)** who showed U.S. corn-ethanol emits more GHGs relative to gasoline if changes in the use of land (e.g., converting forest into crop land) are taken into consideration. This sparked a controversy that reached a fever pitch and both the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) were then authorized to revise their estimate of ethanol's GHG savings to include emissions from indirect land use changes.[7]

This paper addresses the issue of whether corn-ethanol still meets the 20 percent threshold if fuel market leakage is taken into account. We define *market leakage* as a market effect of biofuels in *not replacing* gasoline and petroleum by-products consumption globally[8]. More specifically, the estimated LCA savings in emissions from a gasoline energy-equivalent gallon (GEEG) of ethanol assume ethanol replaces gasoline one to one, that is, it is assumed that there is no market leakage in the fuel market. But there inevitably is leakage in fuel markets, as there are in land and other markets related to biofuels production and consumption.

Our sensitivity analysis results show that one GEEG of ethanol replaces only 0.19 to 0.37 gallons of gasoline. The significant fuel market leakage combined with the land use effect makes one GEEG of ethanol emit as much as 16 percent more carbon than one gallon of gasoline. Thus, our key finding is that the U.S. corn ethanol does not meet the EPA's 20 percent sustainability standard.

Although we focus on the U.S. corn ethanol, the results of this study also apply to the ongoing discussion in the European Union on whether the indirect land use change effect of biofuels should be included in the assessment of biofuels' ability to reduce GHG emissions relative to conventional fuels. As we show, to be consistent, the leakage in other markets should be included, especially that of the fuel market because we show it is very likely to be greater than the leakage in the land market.

The remainder of the paper is organized as follows. The next section defines market leakage and 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 a sustainability standard. Data and procedures used to calibrate the numerical model (extended to oil, petroleum by-products, and the corn market) are presented in Section 3. In Section 4, we present our results. The last section provides some concluding remarks.

MARKET LEAKAGE (INDIRECT OUTPUT USE CHANGE EFFECT) AND CHANGE 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, the term

$$\xi = \frac{e_G - e_E}{e_G} \qquad (1)$$

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, because gasoline is but one of several joint products of crude oil processing, ethanol, in addition to gasoline, also replaces other petroleum by-products, such as distillate fuel oil or kerosene; it is because gasoline and by-products quantities are linked through a fixed production coefficient.[9] This is not reflected in EPA's estimates of CO_2 savings of ethanol. The jointness in production implies a fixed proportion of gasoline and all other petroleum by-products. Denoting β_G and β_B as GEEGs of gasoline and by-products per barrel of crude oil, respectively, the ratio of the quantity of gasoline (G) and by-products (B) is given by

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endogenize the world oil price, which gives rise to the indirect output use change effect in the fuel market.

[5] Earlier works by Drabik and de Gorter (2010) and Drabik et al. (2010) also predicted that U.S. corn ethanol increases global GHG emissions.

[6] The carbon savings of ethanol relative to gasoline in the LCA analysis occur because ethanol comes from feedstocks (e.g., corn) that are able to sequester carbon; there are also carbon savings in the process of producing ethanol.

[7] 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 indirect land use change, but also a revised and substantially lower LCA estimate. As a result, even with indirect 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.

[8] Life-cycle accounting that underpins the 0,1 sustainability thresholds, like the U.S. requirement that corn-ethanol reduce GHG emissions by 20 percent relative to gasoline, assumes one gasoline energy-equivalent gallon of ethanol *replaces* one gallon of gasoline.

[9] We assume 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 imperfect substitutability between oil and other primary energy sources.

$$\frac{G}{B} = \frac{\beta_G}{\beta_B} \qquad (2)$$

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

$$\theta = \frac{e_G + \frac{\beta_B}{\beta_G} e_B - e_E}{e_G + \frac{\beta_B}{\beta_G} e_B} \qquad (3)$$

where e_B denotes CO_2 emissions of a GEEG of by-products.[10] The interpretation of equation (3) is analogous to that of equation (1). A comparison of equations (1) and (3) yields $\theta > \xi$. Intuitively, carbon savings of ethanol are expected to be higher when petroleum by-products are included; this is because in addition to reducing gasoline consumption, ethanol also reduces consumption of the by-products, thus effectively reducing more carbon.

The introduction of E GEEGs of ethanol to the fuel market affects relative prices, and hence also global consumption of gasoline and the petroleum by-products. The change in relative prices results in higher oil consumption in the rest of the world (ROW), which runs afoul of the EPA's implicit assumption that one GEEG of ethanol replaces gasoline one-to-one. To measure the number of gallons of gasoline that are not replaced by ethanol, we define market leakage as

$$L_M = \frac{\Delta G + E}{E} \qquad (4)$$

where $\Delta G < 0$ denotes a reduction in global gasoline consumption due to the introduction of E GEEGs of ethanol. We define market leakage (4) 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.

When E GEEGs of ethanol are placed on the market and consumed (we assume zero ethanol consumption initially), the change in CO_2 emissions is given by[11]

$$\Delta \text{ in global } CO_2 = e_E E + e_G \Delta G + e_B \Delta B \qquad (5)$$

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, obtains

$$\Delta \text{ in global } CO_2 = \underbrace{-\theta\left[e_G + (\beta_B/\beta_G)e_B\right]E}_{\substack{\text{reduction in emissions associated with} \\ \text{consumption of ethanol}}} + \underbrace{\left[e_G + (\beta_B/\beta_G)e_B\right](E+\Delta G)}_{\substack{\text{change in emissions due to} \\ \text{market leakage}}} \qquad (6)$$

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 if ethanol replaced 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. 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

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

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

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

$$= \theta - L_M$$

This result is in line with the finding of **Stoft (2010)**.

Expression (8) suggests that corn ethanol results in a reduction in global carbon emissions if and only if $\theta - L_M > 0$; that is, the emissions savings effect of a biofuel has to outweigh the indirect output use effect. For instance, if $\theta = 0.8$ and $L_M = 0.7$, then net savings of corn ethanol relative to gasoline and corresponding by-products are only 10 percent.

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

[11] 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. It is 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 – 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.

Finally, the quantity (8) can be used to determine whether corn ethanol meets a pre-determined sustainability standard.[12] This entails determining whether

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

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

DATA

We use the numerical model detailed in **Cui et al. (2011)**, but calibrate it to a different set of biofuel policies, namely: a binding mandate combined with a blender's tax credit, an ethanol production subsidy, and a feedstock (corn) production subsidy. All baseline data, their primary sources, or formulas are presented in the Appendix. All relevant data are converted into gasoline-energy equivalents to consistently model the linkages in the fuel market.

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. The U.S. ethanol consumption in 2009 amounted to 11.04 bil. gallons, which represents a 6 percent energy share in total U.S. gasoline fuel consumption. The ethanol blender's tax credit of $0.498/gallon consists of the federal part, $0.45/gallon, and the state part, which averaged $0.048/gallon in 2009 (**Koplow 2009**). The ethanol production subsidy calculated from **Koplow (2009)** is $0.14/gallon in 2008. We assume the same level of the subsidy in 2009.

Corn subsidies in the Unites States totaled $3.79 bil. in 2009 (Environmental Working Group).[13] Of the total, $2.00 bil. were decoupled subsidies. Following **Sumner (2006)**, we assume a coefficient of 0.25 as the degree to which decoupled subsidies are actually coupled. Total production subsidies 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. The average tax on the petroleum by-products we consider equals 33 percent of the gasoline tax.

Following the analysis in **de Gorter and Just (2009b)**, we calibrate the model to a binding mandate (and other policies described above). In this case, 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.[14] Corn and ethanol prices are linked through a zero profit condition for ethanol production; similarly are linked the prices of oil, gasoline, and petroleum by-products.

In the feedstock (corn) market, we explicitly model the market effects of the co-product of ethanol production (Dried Distillers Grains with Solubles, DDGS). (See **Drabik 2011** for details on these effects). Following **Hoffman and Baker (2011)**, we assume 81 percent of DDGS is consumed domestically and the rest is exported.

Our numerical model uses demand and supply curves that exhibited constant price elasticities; this enables us to capture potential non-linear effects due to 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 the Appendix. Owing to the lack of econometric estimates, we assume the demand for petroleum by-products has the same elasticity as the demand for fuel. We assume the supply elasticity of oil in the ROW is 0.15. We do so to obtain a reasonable estimate of demand elasticity for oil in the ROW, -0.29 (this demand elasticity is consistent with the results of a recent meta-analysis by **Havránek et al. 2012**), while imposing that the elasticity of oil import supply facing the United States is 3.00 – a value used in **Cui et al. (2011)**.

Carbon emissions

An oil refinery produces a number of petroleum products, of which gasoline represents 46.1 percent (Table 1). The implied volume of gasoline obtained from one barrel of oil (42 gallons) is thus 0.461 x 42 = 19.362 gallons. The second column in Table 1 presents the implied volumes for other petroleum 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 (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 gives shares of individual petroleum by-products (exclusive of gasoline) in 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 this. First, the volume of 19.362 gallons does not take into account the processing gains. It is not clear, however, how the processing gains are actually distributed among various oil products. Second, before gasoline is sold at retail pump stations, special additives (other than ethanol) are mixed with gasoline to enhance its properties. These additives are produced from petroleum by-products.

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[12] We are grateful to a reviewer for pointing out that the threshold used in inequality (9) is not the same as the EPA threshold; in fact, it is more general. Because we calculate carbon savings of ethanol viz-a-viz gasoline and corresponding petroleum by-products, we cannot use the EPA's standard for comparison, as it relates strictly to gasoline. It is to be noted, however, that this does not affect the ensuing results. It is because had the EPA recognized the additional carbon savings from replacing some petroleum by-products, it would have very likely increased the threshold. This would make it even less likely for corn ethanol to pass the sustainability test.

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

[14] If the tax credit was the binding policy, the fuel price would be equal to the sum of the gasoline price and the fuel tax.

Hence, some volume of the by-products is reshuffled to gasoline, thus making its effective volume per barrel of oil be more than 19.362 gallons.

We calculated 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.[15] The ethanol consumption was 11.04 bil. gallons and imports of additives (not produced from the oil processed in the United States) were 10.73 bil. gallons. Thus, the quantity of gasoline (inclusive of additives) produced domestically is equal to 134.74 - 11.04 - 10.73 = 112.98 bil. gallons. Finally, the actual yield of gasoline per barrel of crude oil, 21.483 gallons, is obtained by dividing the quantity of gasoline produced in the United States and the quantity of oil processed in 2009, 5.26 bil. barrels.

Table 1 Oil products and their carbon emissions

	Refinery yield (share)[a]	Gallons/ barrel	Share in by-products	Adjusted gallons/ barrel	kgCO$_2$/ 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		20.864[c]		404.52
Subtotal for by-products (excluding gasoline)		25.410		23.289		

Note:
[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
[c] Denotes the sum of petroleum by-products in this column.

As we are not able to apportion the processing gains to individual petroleum products, nor are we able to determine how much of each petroleum by-product was 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 volume by the shares reported in the third column in Table 1. Thus, for example, the adjusted volume of distillate fuel oil is equal to 0.445 x 23.289 = 10.355 gallons. We calculate the adjusted volumes only for petroleum by-products that get combusted.

The fifth column shows how much CO$_2$ is released when one gallon of a petroleum product is combusted. The last column of Table 1 gives total CO$_2$ emissions by which each product contributes to a barrel of oil. For example, for gasoline it is 21.483 x 8.91 = 191.42 kg/barrel. The sum of the values in the last column then gives total CO$_2$ emissions of a barrel of oil at combustion, 404.52 kg.

But 404.52 kg CO$_2$ per barrel of oil is an under estimate because it ignores other emissions, for instance, those related to drilling of oil. We thus need to determine CO$_2$ emissions of crude oil corresponding to its life-cycle analysis (LCA). To do that, we use the values given in Table 2. 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. As much as 80 percent of all carbon emissions of gasoline are released at combustion (i.e., tank-to-wheels). We assume this ratio applies also to other petroleum by-products. Thus, we calculate LCA emissions of petroleum by-products as 213.10/0.8 = 264.89kg/barrel, where the value of 213.10 represents the

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

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	$z_{21} = (1-\xi_{21})G'_{WW}$

Note:
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

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); thus, we arrive at 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 scenarios for the carbon savings of corn ethanol relative to gasoline. First, corn ethanol emits 52 percent less carbon emissions relative to gasoline it is supposed to replace. This estimate does not take into account the emissions due to land use change due to biofuels. When emissions from land use change are included, the relative savings of corn ethanol reduce to 21 percent (**EPA 2010**).[16] 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

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

at carbon savings of 79 and 65 percent for the case when emissions from land use change are excluded and included, respectively. Intuitively, the carbon savings should be higher, because one gasoline-energy equivalent gallon of ethanol not only replaces gasoline, but also a corresponding quantity of petroleum by-products.

RESULTS

In this section, we empirically illustrate our theoretical findings. We analyze market effects of three biofuel policies: an ethanol blender's tax credit, a consumption mandate, and their combination. (See **Drabik 2011** for the underlying economics of individual policies). The motivation for choosing the three policies is the fact that they have been used in the United States in different periods of the biofuel era (first, the tax credit alone; then coupled with the mandate; and currently only the mandate as the tax credit for corn ethanol has been abandoned). Moreover, other countries (e.g., the European Union) also use various policies.

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 or 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 blender's tax credit is provided). In this situation, the free market price of ethanol ($1.82/GEEG) is too low to generate any ethanol production.[17] We take the values reported in the first column as benchmark values to be used for estimation of the magnitude of market leakage associated with individual ethanol policies.

In the second column, we present 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.[18] 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 (net) by $0.95/barrel, as does the gasoline price (down by $0.27/gallon). The reduction in the oil price is mitigated by an increase in the market price of petroleum products, however, (up by $0.21/GEEG). It is because the reduction in global oil production results in a decrease in the production of petroleum by-products (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).[19] Ethanol price increase is the same across all three policies, however, as they all share the same level of ethanol consumption. Although the global oil consumption due to the introduction of ethanol decreases 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 first row in Table 4, entitled *Most plausible parameters*, corresponds to the values presented in Table 3.[20] For example, the value 0.812 under the tax credit policy means that 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)).[21,22] Notice that if ethanol replaced gasoline one-t one, then the change in global fuel consumption should be zero. Under the tax credit, one GEEG of ethanol replaces only 1-0.812 = 0.188 gallons of gasoline.

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.[23] The changes in elasticities in the second, third, and forth row are self-explanatory. In the scenario entitled *Inelastic fuel demand*, we assume the elasticity of U.S. demand for fuel to be -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. This implies 23.52 and 21.25 gallons of gasoline and petroleum by-products, respectively per barrel of crude oil.

All scenarios exhibit stable and high levels of market leakage both within and across biofuel policies.[24]

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[17] 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).

[18] This corresponds to $1.27/GEEG of ethanol.

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

[20] We take these elasticities from well known and respected papers in the agricultural and energy economics profession.

[21] 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.

[22] For comparison, Chen and Khanna (2012), report a leakage in the global gasoline market (under a mandate) of 50.1 percent; in Drabik et al. (2010), the market leakage varies between 60-65 percent; and in Drabik and de Gorter (2010) between 64-79 percent.

[23] The coefficients of variations corresponding to "Tax credit", "Mandate", and "Mandate & tax credit" are 6.7, 8.1, and 7.3 percent, respectively. The coefficient of variation for all market leakage estimates in Table 4 is 7.1 percent.

[24] The stability of leakage estimates across policy instruments stems from the fact that we compare for the same level of ethanol

(An exception, perhaps, is the case of very elastic oil supply relative to oil demand in the ROW. Yet, market leakage is quite high, above 60 percent). 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, it does not necessarily mean that global carbon emissions decrease as well. Intuitively, this happens because ethanol is not a carbon-free replacement of gasoline. Recall that the EPA requires that corn-ethanol emits at least 20 percent less carbon relative to gasoline it is assumed to replace.

We estimate the actual carbon savings of ethanol relative to gasoline and corresponding petroleum by-products in Table 5; all values are calculated by taking the difference between the emissions savings effect of ethanol relative to gasoline and petroleum by-products and the market leakage effect reported in Table 4 (see equation (8)). The actual carbon savings of corn ethanol are calculated under two situations. In the first situation, we exclude emissions form indirect land use change on total carbon emissions of ethanol, while in the second situation we include the indirect land use change effect. Because the latest EPA's ruling does include indirect 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 using expression (8) and is equal to a 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 to 37 percent), meaning that the carbon reducing effects of ethanol are difficult to materialize. Second, ethanol does not reduce 100 percent carbon emissions relative to gasoline and petroleum by-products. In other words, a dirty fuel is replaced by a less dirty fuel.

Notice, however, that global carbon emissions decline when the ethanol use is mandated (first row and second column in Table 5). The reduction is only marginal, however, because one GEEG of ethanol reduces only 0.2 percent carbon emissions relative to gasoline and by-products. A more significant reduction (16 percent) is achieved under the mandate and very elastic oil supply curve in the ROW (fourth scenario). Nonetheless, corn ethanol does not meet the EPA sustainability standard of 20 percent (see also footnote 12).

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 the U.S. corn ethanol meets the 20 percent sustainability standard imposed by the EPA.

Such a conclusion warrants some discussion as to under which conditions this result holds. We therefore analyze the threshold market leakage below which our conclusion would not hold true. Suppose for a moment that the EPA's sustainability standard for corn ethanol is a 20% carbon emissions reduction relative to gasoline and corresponding petroleum by-products (albeit the EPA does not consider the by-products). Then rearranging condition (9), the threshold market leakage must satisfy $\max L_M < \theta - \text{sustainabilty standard}$. To obtain a conservative estimate for this threshold, we set θ=0.79 (see Table2) which corresponds to corn ethanol carbon savings relative to gasoline and corresponding petroleum by-products and ignores the iLUC effect. So for given values, our conclusion does not hold, if market leakage is less than 59%. To be more realistic, however, we should consider θ=0.65 (Table 2) which takes into account the iLUC effect. As a result, the threshold market leakage falls to 45%. But this is not the final estimate yet because as we explain in footnote 12, the sustainability standard that recognizes ethanol's savings not only relative to gasoline but also relative to by-products would be higher, hence further reducing the threshold market leakage. In summary, for the market leakage estimates provided in Table 4, it is safe to say that our key conclusion that the U.S. corn ethanol does not meet the EPA's sustainability standard holds.

But the literature provides a range of magnitudes for fuel market leakage that differ from ours.[25] For example, **Chen and Khanna (2012)** find a leakage central value of 50% (with a range of 39%-68%) and **Rajagopal and Plevin (2013)** a range of 30-70%. While the low extreme (and hence less likely) values of these estimates make our conclusion discussable, the central estimates support it.

CONCLUSION

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 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.

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consumption. As a result, the decrease in the domestic fuel price is similar across policy instruments, as is the decrease in the market price of gasoline.

[25] The differences most likely stem from assuming different elasticities; modeling the mandate in a different way than we do (Chen and Khanna 2012); and using a different model structure.

Whether or not consumption of biofuels results in an increase in global GHG emissions depends on two factors. First, the market leakage effect determines the actual rate by which a biofuel replaces a fossil fuel. Our sensitivity analyses show that one gasoline-energy equivalent gallon of ethanol replaces only 0.19 to 0.37 gallons of gasoline. 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 could 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.

We find that the U.S. corn ethanol is unlikely to meet the EPA's sustainability standard not only when the indirect land use change effect of biofuel is considered, but more importantly, also when this effect is not taken into account. Recognizing the presence of carbon leakages of biofuel policies in both the fuel and land markets, we find that one gasoline energy-equivalent gallon of ethanol could emit as much as 16 percent more carbon than one gallon of gasoline.

The empirical evidence presented in this paper suggests leakage from biofuel policy is significant. Leakage from biofuels policies is difficult to address in policy design because a mandate does not help much due to international leakage overriding a potential 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 or REDD scheme, the problem is not always solved by having all countries adopt a biofuels policy. The reason is that all leakage will be "autarky" leakage (i.e., all domestic) but this will likely result in little savings compared to the case if the United States was the only country with the biofuels policy.

Although we focus on the U.S. corn ethanol, the qualitative results of our study are also applicable to the ongoing discussion in the European Union on whether the indirect land use change effect of biofuels should be included in the assessment of biofuels' ability to reduce greenhouse gas emissions relative to conventional fuels. Future research in this area should analyze the fuel market leakages due biofuel policies of not only one country, but of the group of the largest biofuel consuming countries.

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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

Note:
* ROW - rest of the world
Source: calculated

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
Reversal of gasoline and petroleum by-products production coefficients	0.777	0.747	0.764

Source: calculated

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
Reversal of gasoline and petroleum by-products production coefficients	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
Reversal of gasoline and petroleum by-products production coefficients	-12.4	-9.4	-11.1

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

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Appendix 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		$r = (P_{DDGS}*56)/(P_C*2000)$
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	$k = \lambda\beta/(1\text{-}r\gamma)$
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	$P_F = \alpha*(P_E + t/\lambda - t_c/\lambda) + (1\text{-}\alpha)*(P_G + t)$
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 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[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.