Supporting Information For:

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Supplementary Tables

This section provides tabular results that support the main results presented in the main text. Tables SI.1 through SI.5 report the impact of each biofuel policy on ethanol, land markets and fuel markets. Tables SI.6 through SI.9 report additional emissions results for each policy and year. Additional tables support the supplementary methods and supplementary text sections below.

Methods

Numerical Model

General Environment The numerical framework is a static model of two countries with small open economies: the US, denoted D, and the rest of the world, denoted W. The rest of the world, is a collection of small open economies that trade agricultural crops and crude oil with the US. The remaining goods in the economy are assumed to be immobile. Therefore, only the prices of crops and crude oil are set on the world market. The US supports ethanol using the VEETC and the RFS. The sectors impacted by ethanol policies in the US are modeled explicitly while adjustments in the rest of the world are treated in a reduced-form manner. For ease of notation, when describing the US portion of the model, the subscript D is omitted.

Consumer Demand The representative household receives utility from vehicle miles traveled (VMT), denoted M, food (X) and a composite consumption good (C) and is endowed with land ($\bar{A}$) and labor ($\bar{L}$). The household's utility function is represented by a set of nested constant elasticity of substitution (CES) functions:

$$\begin{aligned} U(F,X,C,H) &= \left[\alpha_U M(F,H)^{\frac{\sigma_U-1}{\sigma_U}} + (1-\alpha_U)\, W(C,X)^{\frac{\sigma_U-1}{\sigma_U}}\right]^{\frac{\sigma_U}{\sigma_U-1}} \\ W(C,X) &= \gamma_W \left[\alpha_W C^{\frac{\sigma_W-1}{\sigma_W}} + (1-\alpha_W)\, X^{\frac{\sigma_W-1}{\sigma_W}}\right]^{\frac{\sigma_W}{\sigma_W-1}} \\ M(F,H) &= \gamma_M \left[\alpha_M F^{\frac{\sigma_M-1}{\sigma_M}} + (1-\alpha_M)\, H^{\frac{\sigma_M-1}{\sigma_M}}\right]^{\frac{\sigma_M}{\sigma_M-1}} \end{aligned} \tag{1}$$

where W is a composite of food and other consumption and H denotes fixed costs of driving. σ_U, σ_W, and σ_M are elasticities of substitution that are chosen exogenously. $\alpha_U, \alpha_W, \alpha_M$ are share parameters and γ_W and γ_M are scale parameters that are calibrated. Embedding the VMT decision permits substitutability between fixed costs of driving and blended fuel, allowing fuel economy to be endogenously determined.

The household's budget constraint is given by:

$$P_F F + P_X X + C + H = \bar{L} + \pi_{\bar{A}} + GOV + T \tag{2}$$

where P_F is the price of blended fuel and P_X is the price of food, $\pi_{\bar{A}}$ is the net returns to the land endowment, GOV is a government transfer and T is the terms-of-trade balance (value of crop exports sold less crude oil imports purchased). The wage rate is normalized to one.[1] The household chooses F, M, and C and H to maximize utility (1) subject to (2). The solutions to the resulting first-order conditions yield the uncompensated demand functions for blended fuel, food, the composite good and expenditures on driving.

Fuel Production Blended fuel is produced from gasoline (G) and ethanol (E). Ethanol and gasoline are model as energy equivalent substitutes with the following linear production function:

$$F(G, E) = G + 0.66E \tag{3}$$

which accounts for the energy density of ethanol (21.3 MJ/l) being only two-thirds the energy density gasoline (32.3 MJ/l). Treating ethanol and gasoline as energy equivalent perfect substitutes is consistent with the assumption that consumers are not able to discern the share of ethanol in the blended fuel they are purchasing, and is a common assumption (see for example (de Gorter and Just, 2009)). Our specification contrasts with A. W. Ando and M. Khanna and F. Taheripour (2010) who use model blended fuel production with a CES production function. A CES functional form may be overly restrictive because the share parameters of the function must be fixed to calibration year data, when the share of ethanol in fuel was very small.

The RFS is modeled as a share mandate:[2]

$$E \geq \theta F \tag{4}$$

where θ is the mandated share of ethanol per unit of blended fuel. This specification matches the implementation of the RFS. Although RFS states the total amount of ethanol to be included in the fuel supply, in practice the EPA sets a minimum share of ethanol given projected demand for blended fuel EPA (2010a).

The VEETC, denoted τ, is modeled a subsidy for ethanol. The fuel blender chooses E and G to minimize production costs:

$$P_G G + (P_E - \tau)E \tag{5}$$

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[1] Both C and H are produced one-to-one from labor, so $P_C = P_H = 1$.

[2] Our specification implicitly imposes an efficient RIN market that closes each year (see Bento et al. (2011)).

subject to equation (3) and (4), where P_G and P_E are the prices of gasoline and ethanol respectively. The resulting factor demand functions for gasoline and ethanol, and the price of blended fuel, are functions of the prices of gasoline and ethanol, the share mandate, and the VEETC.

Ethanol is produced according to a Leontief production function:

$$E(Y_E, L_E) = \min\left\{\frac{Y_E}{\lambda_{E,Y}}, \frac{L_E}{\lambda_{E,L}}\right\} \tag{6}$$

where $\lambda_{E,Y}$ and $\lambda_{E,L}$ are exogenous parameters that determine much corn and labor are required to produce a unit of ethanol, Y_E is corn used for ethanol production and L_E is expenditures on labor. Ethanol production is a joint production process also produces 'co-products' which can be used in place of grains in livestock rations. The four co-products we consider, dried distillers grains, corn gluten meal, corn gluten feed, and corn oil are used in food production.[3]

Gasoline is produced with a constant returns to scale CES technology:

$$G(R_G, L_G) = \gamma_G \left[\alpha_G R_G^{\frac{\sigma_G - 1}{\sigma_G}} + (1 - \alpha_G)\, L_G^{\frac{\sigma_G - 1}{\sigma_G}}\right]^{\frac{\sigma_G}{\sigma_G - 1}} \tag{7}$$

where R_G is crude oil and L_G is labor used for gasoline production, σ_G is the elasticity of substitution, and α_G and γ_G are share and scale parameters respectively.

Agricultural Production Net returns to the land endowment are maximized by allocating land to the production of crops, or setting land aside in the Conservation Reserve Program (CRP) in exchange for a rental payment.[4] Cropland can be allocated to the production of corn, soybeans, wheat, hay and cotton. Corn is denoted Y, the vector of other crops is denoted Z and CRP is denoted N.

Letting i index the six uses, $\{Y, Z, N\}$, the allocation of the land endowment is determined by:

$$\pi_{\bar{A}} = \max_{A_i} \sum_i \left(P_i y_i(A_i) - l_i\right) A_i$$

$$\text{subject to:}$$

$$\sum_i A_i \leq \bar{A} \tag{8}$$

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[3] Co-products are produced in fixed proportion to the amount of ethanol produced and are combined in terms of corn and soybean equivalents with the corn and soybeans used in food production. The value of co-products sold is taken as a rebate to the ethanol producer, and is therefore subtracted from the marginal cost of producing ethanol.

[4] Given that pasture includes land used for continuous hay production, our model captures the portion of pasture land most likely to be brought into agricultural production. However, we abstract from other domestic land uses, such as forest and range because between 2002 and 2007 the quantity of land that transitioned between cropland, forestry and range was minor relative to transitions between cropland and pasture (2007 Natural Resources Inventory).

where P_i is the world price of crop i and A_i is the quantity of land allocated to land use i. l_i is the labor expenditures per unit land required to produce crop i and represents aggregate expenditures on all farm inputs including labor, capital, fertilizer and energy.[5]

For crops, the functions $y_i(A_i)$ represent yields; for CRP $y_i(A_i)$ represents the per unit land CRP rental payment in dollars. The yield (payment) functions in (8) are assumed to be linear and decreasing in the quantity of land allocated to each land use (A_i):

$$y_i(A_i) = \beta_i - \delta_i A_i \tag{9}$$

where β_i and δ_i are the intercept and exogenous slope coefficients of crop i's linear yield (payment) function. This specification reflects decreasing returns to expanded agricultural production and decreasing rental payments to land held in CRP.

The first-order conditions of (8) provide the crop supply functions, $Y(\cdot)$ and $Z(\cdot)$, and the optimal allocation of land to crops and CRP. Only corn is used to produce ethanol, while corn, soybeans, hay and wheat are used in food production. Corn, soybeans, wheat and cotton can be exported.

Food Production Food is produced from crops, co-products and labor by competitive firms.[6] The food production function is a set of constant returns to scale CES functions:

$$\begin{aligned}
X(Y_i, L_X) &= \gamma_X \left[\alpha_X L_X^{\frac{\sigma_X - 1}{\sigma_X}} + (1-\alpha_X)\, Q(\cdot)^{\frac{\sigma_X - 1}{\sigma_X}} \right]^{\frac{\sigma_X}{\sigma_X - 1}} \\
Q(Y_X, Z_X) &= \gamma_Q \left[\alpha_{Z2} Z_{X,2}^{\frac{\sigma_Q - 1}{\sigma_Q}} + \alpha_{Z3} Z_{X,3}^{\frac{\sigma_Q - 1}{\sigma_Q}} + (1-\alpha_{Z2}-\alpha_{Z3})\, V(\cdot)^{\frac{\sigma_Q - 1}{\sigma_Q}} \right]^{\frac{\sigma_Q}{\sigma_Q - 1}} \\
V(Y_X, Z_{X,1}) &= \gamma_V \left[\alpha_V Y_X^{\frac{\sigma_V - 1}{\sigma_V}} + (1-\alpha_V)\, Z_{X,1}^{\frac{\sigma_V - 1}{\sigma_V}} \right]^{\frac{\sigma_V}{\sigma_V - 1}}
\end{aligned} \tag{10}$$

where L_X, Y_X and Z_X are labor, corn and a vector of other crops used in food production.[7] σ_X, σ_Q, and σ_V are elasticities of substitution, α_X, α_{Z2}, α_{Z3} and α_V are share parameters, and γ_X, γ_Q and γ_V are scale parameters. Here, Y_X and $Z_{X,1}$ are corn and soybeans used by the food sector net of ethanol co-products.

Nesting food production in this manner allows us to impose sufficient complementarity between labor and crops. Likewise, we can allow for greater substitutability between corn and soybeans than between corn and soybeans and the other crops.

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[5] To make this specification consistent with CRP, we set P_N to one and l_N to zero.

[6] We do not model livestock production explicitly. Rather, food is modeled as a composite of all final food products. Although the livestock sector is emissions intensive, biofuel policies are expected to have a limited impact on emissions from livestock production EPA (2010b).

[7] In the vector Z_X crops are indexed, with the second subscript, as follows: soybeans ($j = 1$), hay ($j = 2$), wheat ($j = 3$) and cotton ($j = 4$).

The food producer chooses quantities of crops to minimize production costs given the food production technology, taking prices as given. The first-order conditions provide the factor demand functions for corn and other crops for food production, and the resulting unit-cost function is the price of food.

Crop Export Demand The rest of the world responds to US ethanol policies only through adjustments in the world prices of crops and crude oil. We model the world demand for US exports of corn, soybeans, wheat and cotton. The inverse rest-of-world excess demand for crop i is given by:

$$\begin{aligned} P_Y &= \gamma_i \left(Y_W\right)^{\frac{1}{\eta_Y}} \\ P_Z &= \gamma_i \left(Z_W\right)^{\frac{1}{\eta_Z}} \end{aligned} \tag{11}$$

where Y_W and Z_W are the rest-of-world demand for US crop exports, the η terms are the rest-of-world excess demand elasticities and the γ terms are scale parameters. Given changes in crop exports, we impute how cropland expands at the expense of non-agricultural land uses, $A_{N,W}$, outside the US.

Similarly, the inverse rest-of-world net supply of crude oil is given by:

$$P_R = \gamma_R \left(R\right)^{\frac{1}{\eta_R}} \tag{12}$$

where γ_R is a scale parameter and η_R is the rest-of-world excess supply elasticity for crude oil. Underlying the rest-of-world excess supply of crude oil is a rest of world demand for crude oil (R_W), that responds to the world price.

Government The government provides a lump-sum transfer to the representative household, the VEETC to fuel blenders and a rental payment to land that is held as CRP ($y_N(A_N)$). Government expenditures are financed by taxes on blended fuel (t_F) and labor (t_L). The government's budget constraint is given by:

$$t_F F + t_L \bar{L} = GOV + y_N(A_N)A_N + \tau E. \tag{13}$$

Equilibrium Conditions An equilibrium consists of a price vector, P_Y, P_Z, P_R, and a government transfer, GOV, such that the world markets for crops and crude oil:

$$\begin{aligned} Y &= Y_X + Y_E + Y_W \\ Z &= Z_X + Z_W \\ R &= R_G \end{aligned} \tag{14}$$

the labor market in the US clear and the government budget (13) is balanced. The terms-of-trade balance in (2) is given by:

$$T = \sum_i \int_{P_i^0}^{P_i^1} Y_{i,W}(P_i)dP_i - \int_{P_R^0}^{P_R^1} R(P_R)dP_R \tag{15}$$

where the prices superscripted 0 are baseline prices and the prices superscripted 1 are prices when an ethanol policy is imposed.

Greenhouse Gas Emissions Total greenhouse gas emissions (GHG) are given by:

$$GHG = \phi_G G + \phi_E E + \phi_Y A_Y + \phi_Z A_Z + \phi_{N,D} A_{N,D} + \phi_{N,W} A_{N,W} + \phi_R R_W \tag{16}$$

where the ϕ terms are GHG emissions released per unit of good or activity, and all quantities and emissions factors are specific to country D unless otherwise indexed.

The impact of the policy on ethanol and emissions is calculated by comparing the model outcomes with the policy in place to of a baseline simulation. The baseline simulation establishes the counterfactual level of emissions and ethanol without the policy of interest imposed, but with pre-existing ethanol policies in place. The policy-based consequential lifecycle emissions savings metric is the total change in emissions divided by the quantity of ethanol added. Using superscripts B and P to represent model outcomes in the baseline and with the ethanol policy in place respectively, the policy-based lifecycle emissions savings are:

$$\frac{GHG^P - GHG^B}{E^P - E^B}. \tag{17}$$

To provide a clear comparison with other lifecycle studies, the policy-based consequential lifecycle emissions savings can be decomposed by sector. Defining $\Delta x = x^P - x^B$ for any good or activity x, an ethanol policy will generate emissions savings if

$$\phi_E + \phi_Y \frac{\Delta A_Y}{\Delta E} + \phi_Z \frac{\Delta A_Z}{\Delta E} + \phi_{A_{N,D}} \frac{\Delta A_{N,D}}{\Delta E} + \phi_{A_{N,W}} \frac{\Delta A_{N,W}}{\Delta E} \leq \phi_G \frac{\Delta G}{\Delta E} + \phi_R \frac{\Delta R_W}{\Delta E} \tag{18}$$

where the left-hand side is the lifecycle emissions of ethanol, and the right-hand side is the lifecycle emissions of gasoline displaced plus emissions from the change in world crude oil combustion.

Economic Model Calibration

Benchmark Economy Table SI.10 presents the characteristics of the US economy for the calibration year of 2003. Table SI.11 reports key calibration parameters. We chose to calibrate using 2003 data because it precedes several anomalous years prior to our period of analysis, where crop and crude oil prices were well above historic levels. Also, our primary data source for agricultural input data, the USDA's Agricultural Resource Management Survey (ARMS), is conducted for each major crop on a rotating quadrennial basis and 2003 is the central year of a four year cycle.

US GDP was roughly \$7.7 trillion. This includes net government transfers to households of \$2.9 trillion, which we assume here is financed from revenue raised from a uniform tax of 36.6% on the labor endowment. This implies an after-tax value of the labor endowment of \$4.8 trillion.[8] The net returns from land holdings comprise the remainder of GDP and are small, \$27.6 billion.

In 2003, 112.68 million hectares of land were allocated to the five crops considered. These crops represent more than 90% of principle cropland harvested and more than 80% of the value of field crop production in 2003 according to USDA National Agricultural Statistics Service (NASS) data. Corn was the dominant crop in terms of land area, at 31.37 million hectares, followed by soybeans, hay, wheat and cotton. A total of 13.57 million hectares were held as CRP. This is the sum of land held in the general sign-up and continuous non-CREP CRP programs and accounts for close to 95% of total land held as CRP, according to the USDA's Farm Service Agency Conservation Reserve Program Statistics (CRPS). We exclude those categories of CRP land which are not likely to be converted back into crop production, due to the higher rental payments that are received for the services provided, such as rare habitat conservation, riparian buffers, etc. The average CRP rental rate was \$114.48 per hectare.[9] Crop prices represent national average prices (paid to the farmer) reported to the NASS. Average yields in the US for corn, soybeans, hay, wheat and cotton are also from NASS.

Blended fuel consumption was 16,076.6 billion MJ (499.97 billion liters), of this regular gasoline made up 15,855.66 billion MJ (490.28 billion liters). This implies that 3.12 billion barrels of crude oil was used for gasoline in 2003, which is consistent with the US Energy Information Administration's (EIA) US Crude Oil Supply & Disposition (CSD) dataset.[10] Total ethanol consumption was 220.91 billion MJ (10.39 billion liters) according to the US Federal Highway Administration's Highway Statistics 2003 (FHWA).

The price of regular gasoline, \$7.03 per 1000 MJ (\$0.23 per liter), is the consumption weighted US average

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[8] These figures were taken from the US Bureau of Economic Analysis National Income and Product Accounts (NIPA) dataset.

[9] This value was computed from the CRPS and represents the weighted average annual rental payment to land in the general sign-up and non-CREP continuous sign-up programs.

[10] Given that this represents crude oil for US gasoline whereas the CSD presents total crude oil, there are some additional statistics necessary to calculate this figure. These come from the US EIA's Gasoline Components History (GCH) and US Blender Net Input (BNI) datasets.

spot price for all grades of conventional gasoline from the EIA's Annual Energy Review 2008 (AER). We compute a spot price for ethanol in 2003 of \$16.5 per 1000 MJ (\$0.35 per liter), which is the marginal cost of ethanol production less the value of co-products sold to food producers. This is very close to the average 2003 spot price for deliveries to Omaha, Nebraska of \$0.36 per liter according to Nebraska's Unleaded Gasoline and Ethanol Average Rack Prices data.[11] Given benchmark quantities and prices of gasoline and ethanol, the 2003 price of blended fuel is \$7.07 per 1000 MJ (\$0.41 per liter), inclusive of the VEETC.

Consumer We specify elasticities of substitution between miles and non-mile expenditures, σ_U in (1), of 0.50, between food and the composite good, σ_W in (1), of 0.09, and between fuel and non-fuel expenditures on driving, σ_M in (1), of 0.21. These imply a calibrated own-price elasticity of demand for miles of -0.53, an own-price elasticity of demand for food of -0.12, and an own-price elasticity of demand for blended fuel of -0.34, respectively.

Our calibrated own-price elasticity of demand for miles is broadly consistent with literature values for the (negative) of the elasticity of VMT with respect to the price of fuel. Summaries of this literature (see De Jong and Gunn (2001); Graham and Glaister (2002); Goodwin et al. (2004)) report means for short-run estimates between -0.10 and -0.26 and long-run estimates of -0.26 and -0.31. More recent estimates (Small and Dender, 2007) report short-run elasticities between -0.045 and -0.022. We target an average short-run estimate of this elasticity of -0.09 across all of the years of our analysis, 2003-2015, which is well within the central estimates provided by the literature and consistent with Parry and Small (2005). Given that we assume that fuel expenditures represent 40% of the total cost of driving, our calibrated own-price elasticity of demand for blended fuel given this -0.09 target is -0.22, which is also consistent with empirical estimates (Small and Dender, 2007; DOE, 1996).

Estimates of the own-price elasticity of food demand are considerably more sparse. Our estimate is roughly consistent with the estimates of Seale et al. (2003), who report own-price elasticity for a broad consumption group of "food, beverages and tobacco" in the range of -0.075 to -0.098.

The share of crop expenditures on food to the total value of food, assumed to be 0.19, is taken from the USDA ERS *Marketing Bill and Farm Value Components of Consumer Expenditures for Domestically Produced Farm Food*, as the value of farm products per food dollar spent. This assumption allows us to calibrate L_X used in food production. Calibration year crop production and export shares, as well this expenditure ratio, imply the representative agent spends 0.035 of his/her income on food. Calibration year data on fuel prices, fuel quantities, and miles-traveled, and assuming that the share of fixed costs of driving

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[11] Historic ethanol price data is limited. Most spot prices for ethanol are reported as the price of free-on-board deliveries to various rural locations in the Midwest, where ethanol has historically been produced. Spot prices to locations outside of the Midwest exist only for the last few years. Since our spot price for regular gasoline reflects the national average, it is necessary to adjust the non-corn input expenditures accordingly.

to total costs of driving was 0.60 (see below), imply that the share of income spent on VMT was 0.065. We note that these expenditure shares are lower than those computed from the US Bureau of Economic Analysis' (BEA) for 2003 of 0.091 and 0.082 respectively.[12] However, we believe that precisely calibrating the relationship of fuel prices to the price of miles-traveled and the relationship of crop prices to the price of food is of greater importance for determining how the RFS impacts equilibrium prices.

Gasoline Production We assume an elasticity of substitution between crude oil and labor in the production of gasoline, σ_P, of 0.06. This was selected to approximate a perfectly complementary relationship between crude oil and labor in the production of gasoline. The price of gasoline faced by the fuel blender is calibrated to the average spot price for conventional, regular grade gasoline in 2003.[13]

Ethanol Production The per unit ethanol input requirements in equation (6), are calibrated to reflect an average ethanol production facility in the US. In 2003, we assume that the corn to ethanol conversion ratio is 2.56 kg per liter (GREET 1.8c Wang (2009)). We also assume that with each liter of ethanol co-products equivalent to 0.7 kg corn and 0.03 kg soybeans are produced (GREET 1.8c Wang (2009)).

To construct parameters for a national average ethanol producer, we consider four ethanol production technologies, which are combinations of conversion technology (wet or dry milling) and fuel source (natural gas or coal). These categories are used because wet milling and dry milling are inherently different technologies, produce different co-products and have different corn and energy requirements. In 2003, dry mills fired by natural gas and coal account for 39.4% and 12.9% of total ethanol production respectively. Wet mills fired by natural gas account for 5.4% of total production and wet mills fired by coal make up the remaining 42.3%. These shares are derived from ethanol plant start up dates reported by the EPA (2010b).

Labor inputs to ethanol production are calculated as total expenditures on energy, transportation costs, labor and capital for ethanol production. Following Farrell et al. (2006), we assume that the energy requirements of ethanol production are 13.2 MJ/liter, which represents a combination of natural gas, coal and electricity. Average expenditures on labor and capital for ethanol production are assumed to be 0.0053 \$/liter and 0.063 \$/liter. These values are consistent with values reported by an industry survey (Shapouri and Gallagher, 2005).

We estimate the quantity of co-products produced per unit ethanol using equations from GREET 1.8c Wang (2009). In the benchmark 0.52 kg of distillers' grains, 0.03 kg of corn gluten meal, 0.13 kg

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[12] These small differences in expenditure shares are likely due to definitional differences between the national accounts data and those implied by our model. The food share from the BEA is total expenditures in the 'Food' sub-heading divided by total GDP, less net exports. The VMT share is the sum of 'Motor vehicle and parts', 'Gasoline, fuel oil, and other energy goods', and 'Transportation' sub-headings divided by total GDP, less net exports.

[13] Average here means population weighted average price of PADDs 1, 3, and 5. PADDs 1, 3, and 5, are considered as these are the PADDs for which spot price data is readily available. Combined these three PADDs account for 69% of the total US population.

of corn gluten feed and 0.02 kg of corn oil are jointly produced with each unit of ethanol. Consistent with the EPA (2010b), we assume a kilogram of distiller's dried grains displaces 0.95 kilograms of corn and 0.05 kilograms of soybeans. A kilogram of corn gluten feed displaces 1.53 kilograms of corn and a kilogram of corn gluten meal displaces 1.0 kilograms of corn. We allow corn oil to displace corn based on its economic value in 2003, such that \$1 of corn oil displaces \$1 of corn.[14]

Transportation costs incurred by the ethanol producer are also accounted for. First, we assume that the cost of shipping ethanol to its final destination is incurred by the ethanol producer. The cost of shipping ethanol is \$1.5 per 1000 MJ (\$0.032 per liter), which is the PADD average tariff plus rate plus fuel surcharge per unit ethanol weighted by PADD level ethanol consumption. We also assume that the cost of shipping co-products to their final destination is subtracted out from the revenue the ethanol producer receives from selling co-products. The average cost of shipping co-products is 0.029 \$/kg, in constant 2003 dollars. This value is calculated using data on rail costs for transporting DDGs from data compiled by the USDA.

We estimate transportation costs based on USDA data for the average tariff rate plus fuel surcharge per unit ethanol delivered to each PADD, and the rail costs for transporting co-products. Both data series are compiled by the USDA from freight companies (BNSF, UP, CSX, and NS) websites for May 2010. To calculate the average ethanol transportation costs from the USDA data, we approximate the percent of the national total refinery and blender net inputs of fuel ethanol by PADD using data from the EIA on Refinery and Blender Net Inputs of Fuel Ethanol by PADD for the years 2000-2009. To calculate the average costs of shipping co-products from the USDA data, we take an average across all data points and assume that 30% of co-products are transported locally at zero cost to the ethanol plant.[15]

RFS Share Mandate The RFS share mandate, θ, is computed by partially solving the model while treating several of the model outputs from the estimated baseline as fixed. First, we predict the amount of corn required to meet the additional production of ethanol given the quantity of ethanol mandated by the RFS. From this estimated change in corn production, we estimate the resulting change in crop prices, as well as the change in the net returns to the land endowment. From the change in the price of corn, impute the resulting change in the price of ethanol, regular gasoline and crude oil, and thus also the change in the price of blended fuel and VMT. Using these projections, we are able to generate an estimate of final total blended fuel demand, conditional on the RFS. Dividing the published RFS volumes by estimated total blended fuel demand provides an estimate of θ.

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[14] We use this method because corn oil is utilized for much more than just an animal feed, and therefore the typical displacement ratio methods used are not reflected in the historic prices of the two products (Shapouri and Gallagher, 2005).

[15] The USDA data reports the tariff rate plus fuel surcharge per unit of co-products between various origin and destination cities.

Land Use Allocation To construct the per-unit land labor expenditures for agricultural production (l_i in equation (8)), we aggregate expenditures on four broad input categories: labor, capital, energy and fertilizer (Table SI.12). Expenditures on labor and capital are from the USDA's Commodity, Costs and Returns (CCR) dataset. Capital expenditures include interest on operating capital and the capital recovery of machinery and equipment. Labor expenditures include the wages and the opportunity costs of unpaid workers.

We construct energy and fertilizer expenditures from detailed input use data and subsequently use this data to calculate crop specific emissions factors (discussed below). Our estimates for energy expenditures are aggregate expenditures on diesel, gasoline, natural gas, electricity and liquefied petroleum gas. Diesel use for each crop was derived from West and Marland (West and Marland, 2002) and Nelson et al. (Nelson et al., 2009). Crop specific use of the other energy sources were derived from the lifecycle analysis literature (Farrell et al., 2006; Hill et al., 2006; Piringer and Steinberg, 2006). Fertilizer expenditures represent expenditures on all variable inputs that are not categorized as energy, capital or labor and are constructed from two main sources. First, expenditures on nitrogen, phosphorus, and potassium fertilizer, pesticide and seed are calculated using crop level input use data from ARMS and national prices from the USDA's Fertilizer Use and Price data.[16] Second, expenditures on other variable inputs are from the CCR.[17] Fertilizer expenditures are disaggregated in the lower panel of Table SI.12.

Land Supply Elasticities The six δ_i in (9) are taken from Bento and Landry (2011). These were estimated in order to match the supply response of the US land market for each year that the model is run, using the literature elasticities reported in Table SI.13 as inputs. This estimation strategy provides two main benefits. First, it ensures proper calculation of the counterfactual amount of ethanol that would be produced in the absence of various biofuel policies. Second, it allows for the proper calculation of the domestic emissions from agricultural and land use adjustments.[18] For 2003, the six β_i in (9) were chosen to match the yields reported in Table SI.10. For later years, each β_i is adjusted given exogenous growth in crop yields.

Rest-of-world Crude Market The model framework presented above considers the excess supply of crude oil going to the US for gasoline consumption, R. To calibrate the elasticity of excess supply facing US gasoline producers and to calculate the impact of the RFS on rest of world crude oil consumption we rely on a simple model of the international crude oil market. An important feature of our framework is that we

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[16] Input data for hay is not available in the ARMS, so fertilization rates were collected from extension reports from institutions in major hay producing regions. Application levels were based on recommendations given a medium or optimal soil test.

[17] This includes expenditures on soil conditioners, manure, custom operations, repairs, purchased irrigation water, taxes and insurance, and general farm overhead.

[18] Refer to Bento and Landry (2011) for a detailed exposition of our estimation strategy, as well details on model validation given this approach.

incorporate all US crude oil demand for purposes other than gasoline production, as well as all US supply of crude oil, in our specification of the international crude oil market. This assumption simplifies the numerical model and the exposition of leakage sources.[19]

Imposing market clearing in the international market for crude oil implies:

$$R = D_{Gas}^{US} = S_{Crude}^{ROW} + S_{Crude}^{US} - D_{Crude}^{ROW} - D_{Dist}^{US} - D_{Other}^{US} \tag{19}$$

where, D_{Gas}^{US} is the amount of crude oil demanded for gasoline in the US market, D_{Dist}^{US} is the amount of crude oil demanded for distillate fuels in the US market, D_{Other}^{US} is the amount of crude oil demanded for all other crude products (which includes residual fuels, jet fuel, kerosene, LPG and other petroleum products) in the US market, D_{Crude}^{ROW} is the amount of crude oil demanded in the ROW market (for all products), S_{Crude}^{ROW} is the amount of crude oil supplied by the ROW, and S_{Crude}^{US} is the amount of crude oil supplied by the US.[20]

Differentiating this equation with respect to the price of crude oil and solving for the elasticity of excess supply facing US gasoline producers, η_R, we have:

$$\begin{aligned}\eta_R = \eta_{S,Crude}^{ROW}\left(\frac{S_{Crude}^{ROW}}{D_{Gas}^{US}}\right) + \eta_{S,Crude}^{US}\left(\frac{S_{Crude}^{US}}{D_{Gas}^{US}}\right) \\ - \eta_{D,Crude}^{ROW}\left(\frac{D_{Crude}^{ROW}}{D_{Gas}^{US}}\right) - \eta_{D,Dist}^{US}\left(\frac{D_{Dist}^{US}}{D_{Gas}^{US}}\right) - \eta_{D,Other}^{US}\left(\frac{D_{Other}^{US}}{D_{Gas}^{US}}\right).\end{aligned} \tag{20}$$

To calibrate η_R using (20) we use data for 2003 quantities from the EIA's International Energy Statistics. The quantities for each of these components of the crude oil market, following the decomposition above, as well as the shares of each component to the quantity of crude demanded for gasoline in the US is reported in the first two columns of Table SI.14. In 2003, total world crude considered in our framework is 4,545.8 billion liters (28,954 million barrels).[21] The rest of the world is the primary supplier of crude oil, contributing 4,046.2 billion liters while the US supplies 499.6 billion liters. On the demand side, ROW crude demand totals 3,419.5 billion liters. US crude oil demand makes up the remainder, with roughly 44% (490.3 billion liters) of total US crude oil demand going to gasoline production.

The final column in Table SI.14 reports the central literature values for the elasticities on the right-hand side of (20) as well as the resulting elasticity of excess supply facing the US gasoline producer (first row), η_R. We use short-run elasticity estimates from the literature because these elasticities are used to quantify the

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[19] Separating US demand for crude products in this manner is a definitional assumption only. As discussed in the next section, the excess supply elasticity faced by US gasoline producers is calibrated to account for US crude demand for purposes other than gasoline production and should therefore have no impact on the overall adjustments in US or ROW crude oil demand.

[20] We use EIA definitions regarding the quantity of crude oil going to the the production of each petroleum product.

[21] Our estimate here is slightly below (138 million barrels) the EIA estimate of total world crude consumption because we ignore gasoline used for non-transportation purposes in the US. Keeping the market shares constant, we adjust the total size of the crude market to reflect this difference. As a result, the quantities reported in Table SI.14 will be slightly below the values reported by the EIA.

annual response to a change in the yearly average price of crude oil. In this time frame, we can expect both supply and demand infrastructure adjustments, such as adjustments in operable crude oil refinery capacity or oil recovery and transportation infrastructure, to be relatively fixed.

We chose elasticities for the US and ROW supply of crude oil of 0.045 and 0.035, respectively. The resulting elasticity of total world crude supply is 0.037 which is consistent with values estimated and used by the literature which range from 0.01 to 0.06 (Krichene, 2002; Smith, 2009; OECD, 2004). Given what appears to be a structural change in this market since at least 1973, we give greater weight to analyses that use more recent data, which appear to suggest smaller elasticities, especially with respect to OPEC sourced crude oil, than in the past. We choose a slightly higher elasticity for US supply than ROW supply; an assumption that is supported by the literature (Ramcharran, 2002; Greene, 2010).

Our value for the elasticity of world crude oil demand, -0.02, is within the range of elasticities found in the literature. Estimates, and values used in the literature, of the elasticity of crude oil demand range from -0.01 and -0.17, with most estimates falling in the range of -0.02 to -0.06 (Krichene, 2002, 2005; OECD, 2004; Gately, 1984; Gately and Huntington, 2002). In our model, the elasticity of ROW crude demand is used to calculate the change in rest of world crude oil use. A number of studies (Gately and Huntington (2002); Dargay and Gately (1995, 2010)) have noted that the demand response for crude products to changes in crude prices, particularly in developed countries, is more limited for price decreases than price increases. Since the RFS will always decrease the price of crude oil, we select a conservative estimate closer to the lower end of the estimates reported in the literature to reflect this asymmetry.

In the absence of comparable short-run estimates for crude demand for distillate fuels and other petroleum products we use an elasticity of -0.02 for each of these components of demand. Since these two components, in addition to total ROW demand for crude oil together make up 90% of total world crude oil demand, it is reasonable to expect that the net elasticity across these components will be very close to the elasticity of world crude demand.

Given our chosen elasticity values and the 2003 quantities of each crude oil market component, we calibrate (12) to reflect an excess supply elasticity for crude oil of 0.5 in our central case. As discussed, there is a broad range of estimates for elasticities of crude oil supply and demand in the literature. To account for this range, we consider values of 0.25 and 0.75 as lower and upper bounds for η_R in sensitivity analysis. One possible way to think about these bounds, would be to proportionally scale the corresponding elasticities for rest-of-world demand and supply of crude oil. For example, when we impose an elasticity of excess supply elasticity of 0.75 the elasticity of rest of world crude crude oil demand of -0.03.

Rest-of-world Crop Demand The crop export demand elasticities, η_i in equations (11), are set to -0.65, -0.60, -0.55, and -0.75 for corn, soybeans, wheat and cotton respectively, which represent the central values reported in Gardiner and Dixit (1987).

Rest-of-world Land Use In absence of a fully specified world land use model, we linearly relate reductions in US crop exports to reductions in world agricultural land. Specifically, we assume that 44%, 50%, 47% and 50% of reduced US corn, soybean, wheat and cotton exports are replaced by expanded agricultural production in the rest of the world at non-US average yields. These shares are given by:

$$\gamma_{ROW,i} = \frac{-\eta_{S,i}^{ROW} S_i}{\eta_{D,i}^{ROW} D_i - \eta_{S,i}^{ROW} S_i} \tag{21}$$

where $\eta_{S,i}^{ROW}$ and $\eta_{D,i}^{ROW}$ are the rest-of-world elasticities of supply and demand for crop i, and D_i and S_i are the rest-of-world demand and supply for crop i. The elasticity values are from the FAPRI Searchable Elasticity Database and the supply and demand quantities are 2003 values reported by the USDA's Foreign Agricultural Service (FSA) Production, Supply and Distribution Online (PSD) dataset.

The share of reduced US crop exports replaced by expanded agricultural production are broadly consistent with range of values implied by earlier studies by Searchinger et al. (2008) and the US EPA (2010b).[22] More recent studies, such as Hertel et al. (2010), argue that the earlier analyses overestimate world land use change because they fail to account for factors that may mitigate a portion of the expansion in world agricultural production such as price induced yield improvements and crop demand adjustments. To address the uncertainty in the literature, as sensitivity analysis we consider high and low cases where the percentage of US crop exports replaced by expanded world production for each crop are increased and decreased by 20% from the central value. The high case represents a world with a more inelastic world demand for agricultural products and where yields respond inelastically to price increases. The low case represents the case where reductions in crop demand and price induced yield improvements soften the link between reduced US exports and rest-of-world land use change.

Intertemporal Dynamics The numerical model generates a time path of economic outcomes at one year intervals between 2009 and 2015. To account for underlying dynamic trends that alter our emissions calculations, we allow for domestic and international income, average fuel economy, crop yields, average crude oil prices, and ethanol production technology to adjust exogenously.

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[22] The results of Searchinger et al. (2008) imply that 50%, 82% and 52% of reduced US corn, soybeans and wheat exports are replaced by expanded production worldwide. Similar percentages are implied in the US EPA (2010b) study for corn and soybeans in 2015, 65% and 67% respectively. However, world land allocated to wheat declines in this year, despite reduced US wheat exports.

We assume that household income grows at an annual rate of 1%. International income growth is modeled through increased world demand for US crop exports. Following historical average annual growth in crop exports over the years 2000-2009, we allow exports to grow by 1.13%, 2.70%, 0.21%, and 1.65% for corn, soybeans, wheat, and cotton, respectively.[23]

We allow fuel economy to exogenously increase by 0.22% per year. This trend is based on fuel economy projections from the 2002 National Research Council analysis of CAFE standards (National Research Council, 2002) and vehicle fleet composition from (Bento et al., 2009).

The price of crude oil generally follows the Reference Scenario projections of EIA's Annual Energy Outlook (AEO) 2010, increasing monotonically from 63.37$/bbl in 2009 to 73.85$/bbl in 2015 (in constant 2003$). Given the sharp spike in crude oil prices in 2008, followed by the precipitous decline in 2009, we take the average of the two prices as our 2009 crude oil price. To capture the strictly increasing path of crude prices in the AEO, we linearly project crude oil prices between 2010 and 2012. For the years 2013 to 2015 we use the values directly from the AEO (adjusted to constant 2003$). In generating the counterfactual baseline this price path is exogenously imposed. When we simulating the impact of ethanol policies, the price of crude oil is allowed to endogenously adjust from this initial level, according to (12).

In 2009 baseline crop yields match observed average US yields taken from NASS. For the years 2010-2015, yields for all crops except hay follow 2010 USDA *Agricultural Projections to 2019*. Hay yields are allowed to increase by the average annual growth rate between the years 1990-2008, or 0.24% per year. CRP rental rates increase by 2% a year, matching historic trends reported in the CRPS. Improvements in international crop yields also follow USDA's 2010 Agricultural Projections.

We allow ethanol production technology to improve following US EPA projections (EPA, 2010b). We allow the labor requirements of ethanol production to fall by roughly 50% between 2003 and 2015. These improvements are driven by increasing energy efficiency of ethanol production due to a projected expansion in efficient dry mill ethanol production (EPA, 2010b). The corn to ethanol conversion ratio also improves. In 2015, the average ethanol conversion efficiency is 0.42 liters/kg, which is 6% higher than the 2003 value.

Projections for baseline total crude oil consumption in the rest of the world are from the International Energy Outlook (IEO) 2009 Reference Case. The IEO provides estimates for 2005 and 2006 and projections for 2010 and 2015. We linearly interpolate values of the years between the reported values. To calculate total petroleum consumption in the rest of the world we take the difference between world consumption and US consumption. The IEO projections do not break down total liquids consumed by type (gasoline, distillates, other). Therefore, we assume that the ratio of each petroleum type to total petroleum consumption is fixed at its 2003 value from 2003 to 2015. We calculate the 2003 shares using data from the EIA's International

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[23] Calculated using data from the USDA's PSD dataset.

Energy Statistics. This assumption is based on historic trends, which show that the shares of total crude consumption of each crude product are close to fixed. Between 2003 and 2007, the share of total crude consumption for any crude product changed by no more than 1% in the rest of the world.

Emissions Calculations

The emissions factors corresponding to the ϕs in equations (16) are (18) are presented in Table SI.15 and are described in detail below. For each product or activity, we account for the release of three major greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) measured in units of carbon dioxide equivalents (CO_2e).[24] For all emissions factors, we abstract from infrastructure related emissions. For example, we measure the emissions from the operation of an ethanol production facility, but do not include emissions from the construction of, or the raw materials used to construct, the facility itself. As a result, our emissions system boundary is slightly more restrictive than that of earlier lifecycle analyses (see for example, Farrell et al. (2006); Hill et al. (2006)), but consistent with the US EPA (2010b).

Overview The marginal emissions coefficient for gasoline, ϕ_G, is inclusive of the emissions from both gasoline consumption and production. In contrast, we consider only the emissions from ethanol production, $\phi_{E,M}$, given that the carbon stored in ethanol, and released during ethanol combustion, is absorbed from the atmosphere during the growth of corn (IPCC, 2007). The agricultural production emissions coefficients, ϕ_Y and ϕ_Z, include emissions from the production of agricultural inputs, such as fertilizer and pesticides, as well as on-farm emissions.[25] All of these emission coefficients, as well as the coefficient on crude oil, ϕ_R, are positive, reflecting the fact that these activities generate GHG emissions. In contrast, the emissions coefficients of non-agricultural land uses, $\phi_{N,D}$ and $\phi_{N,W}$, are negative, reflecting the annual emissions benefits from the uptake of atmospheric carbon by biomass (such as the growth of forest or grasslands) and through increased carbon sequestration in soils (Fargione et al., 2008). These benefits are lost when non-agricultural land is brought into agricultural production. The carbon benefits of non-agricultural land differ between the US and the rest of the world, because the carbon stocks of CRP are limited because these lands have historically been cleared for agricultural production and tend to be held as grasslands, while it is likely that expanded agricultural production in the rest of the world will take place at the expense of previously undisturbed lands with much larger carbon stocks, such as forests or shrubland (see for example EPA (2010b), Searchinger et al. (2008) and Fargione et al. (2008)).

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[24] We use global warming potentials from IPCC Third Assessment Report.

[25] These are emissions that arise from interactions between agricultural soils and farm inputs and fossil fuel combustion.

Gasoline The lifecycle emissions of gasoline, ϕ_G, are 93.0 gCO_2e/MJ (3.0 $kgCO_2e$/liter), which is the baseline lifecycle emissions for US gasoline estimated by NETL (2008). This factor is used by the EPA in the Regulatory Impact Analysis of the RFS, as well as the RFS Final Rule, and includes emissions from crude oil extraction, transport and refining, the transportation and distribution of finished gasoline, and tailpipe emissions (NETL, 2008).[26]

Ethanol Production and Combustion The lifecycle emissions from ethanol production are assumed to be 26.6 gCO_2e/MJ. This factor assumes a representative natural gas fired dry-mill ethanol plant, consistent with the US (EPA, 2010b). We also account for the release of CH_4 and N_2O from ethanol combustion, which totals 0.8 gCO_2e/MJ (EPA, 2010b). Combining, ϕ_E is 27.4 gCO_2e/MJ (0.58 $kgCO_2e$/liter).

We consider only natural gas fired ethanol production for our emissions analysis because the construction of additional coal fired ethanol production facilities is likely to be limited by the RFS legislation, because ethanol produced by these facilities is unlikely to achieve the 20% lifecycle emissions reduction threshold (EPA, 2010b). While we do account for the make up of US ethanol production in the economic model, for our emissions analysis we consider the "marginal" or additional production of ethanol, which we assume occurs in natural gas fired dry mills. Our ethanol production emissions factor is notably lower than an US average emissions factor for ethanol production because coal fired ethanol production is not considered in our emissions analysis.

Rest-of-world Crude Oil Consumption To calculate emissions related to changes in rest of world crude oil consumption, we account only for the emissions from changes in crude used to produce gasoline and distillate fuels, and exclude changes emissions from crude going to other crude products (here defined as including residual fuel oils, jet fuel, LPG and other miscellaneous products). We are therefore considering emissions from approximately 47% of the world crude oil market.[27] Excluding emissions from other crude products is a conservative assumption that allows us to isolate adjustments in rest-of-world crude oil consumption related to the transportation sector that are most likely to have first-order implications for changes in greenhouse gas emissions resulting from the RFS. This assumption is discussed in detail below.

Crude oil is refined into a variety of products that are used by several energy and industrial sectors. Other crude products are used predominantly as factors of production or for non-passenger vehicle transportation purposes, and may not be combusted (in the case of lubricants or crude used for manufacturing). Ideally, to compute the total change in emissions related to changes in crude oil, we would like to specify a detailed

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[26] Refining emissions consist of emissions from the production and consumption of purchased energy, still gas combustion, hydrogen production, and flaring and venting.

[27] In 2003, total crude used for purposes other than US gasoline production totaled 4,055 billion liters. Of this, US distillates totaled 5.5% while ROW gasoline and distillates totaled 16.2% and 25% respectively.

model of the energy and other end-use demand sectors that consume all crude products. This is beyond the scope of this paper, and, as such, we simply assume no change in emissions resulting from other crude products. This is a conservative estimate in the sense that we are assuming the smallest possible change in emissions related to transportation sector adjustments.

To understand why this is, consider the following example of how one would ideally like to compute the change in emissions for one portion of other crude products, residual fuel oil, which is consumed by the electricity sector or by industrial users for energy purposes. Equilibrium in the market for electricity is characterized by:

$$D_{Elect} = S_{Resid} + S_{Other} \tag{22}$$

where: D_{Elect} is total demand for electricity, S_{Resid} is the amount of residual fuel oil supplied by crude refiners for electricity generation, while S_{Other} is the quantity of electricity supplied by sources other than residual fuel oil. If the RFS lowers the price of gasoline, there will be two adjustments in this market that result, a demand-side adjustment, and a supply-side adjustment.

In the case of a demand-side adjustment, a fall in the price of gasoline will lead to a fall in the price of crude oil and consequently the price of electricity. This will push up the left-hand-side of (22), total demand for electricity, leading to additional emissions. However, demand-side adjustments are likely to be very small for the final end-use of energy, since the elasticity of demand in these sectors tends to be very small. For example, residential demand for energy has been found to be very inelastic, particularly in developed countries and in response to price reductions (Haas and Schipper, 1998). Since demand-side adjustments are likely to be small, the increase in emissions due to these adjustments will also be small.

With respect to the supply-side, note that a fall in the relative price of S_{Resid} as a result of the RFS, will lead to substitution from S_{Other} to S_{Resid}, given no change in D_{Elect}. At the margin, this will imply a reduction in emissions from S_{Other} together with an increase in emissions from S_{Resid}. If the crude product displaces a dirtier alternative then this supply-side substitution will result in a slight decrease in emissions. However, if the crude product displaces a cleaner alternative, then this supply-side substitution will imply an increase in emissions. In the case of electricity markets, the alternative will most likely be natural gas or other renewable sources, which is a cleaner alternative relative to residual fuel oil, and so this supply-side margin of adjustment will imply more emissions.[28]

Since both demand and supply-side adjustments in the electricity market are likely to lead to emissions increases, our approach which ignores them entirely will be conservative. Finally, while we have considered the case for residual fuel oil in our hypothetical exposition here, we note that with respect to the other

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[28] A recent study has shown that the demand for residual fuels has been highly responsive to the price of crude oil specifically because of the presence of non-crude energy sources, such as natural gas (Dargay and Gately, 2010).

three components of other crude products (jet fuel, LPG and other miscellaneous products), that similar arguments persist. In the case of 'other petroleum products', which account for roughly a third of other crude products, many of these products are used as lubricants or for chemical manufacturing and not actually combusted. Therefore, the emissions impact will be virtually negligible irrespective of demand or supply-side adjustments.[29]

Crude Oil Emissions Factors

To calculate the emissions from rest-of-world crude oil consumption, we account for changes to each component of the world market for crude oil separately (as discussed above) using fuel specific emissions factors from the EIA's Voluntary Reporting of Greenhouse Gases Program. These emissions factors capture only the direct release of CO_2 from the combustion of petroleum fuels, not the emissions resulting from the refining of crude oil into the final products.

Accounting for emissions only from changes in crude used for gasoline and distillate fuels, the average emissions factor for rest of world crude consumption is 2.6 $kgCO_2e$/liter (408 $kgCO_2e$/barrel). This represents the emissions per liter of distillate fuels and motor gasoline weighted by the rest-of-world market shares of these fuels in 2003. The market shares for gasoline (32%) and distillate fuels (68%) are calculated using data from the EIA's International Energy Statistics. The emissions factor for crude used for gasoline production in the rest of the world is 2.4 $kgCO_2e$/liter (374.2 $kgCO_2e$/barrel). The emissions factor for distillate fuels is slightly higher 2.7 $kgCO_2e$/liter (426.3 $kgCO_2e$/barrel).

Agricultural Production To construct ϕ_Y and ϕ_Z we consider on-farm sources of emissions, which include agricultural N_2O and emissions from energy use and liming, as well as emissions from agricultural input production. N_2O emissions from agricultural production are calculated using methods and default parameters from the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). These methods map nitrogen additions to agricultural soils, from synthetic fertilizers and crop residues, to N_2O emissions.[30] Crop specific synthetic fertilizer application rates are from our agricultural dataset. Nitrogen additions from

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[29] With respect to jet fuel, however, a few additional remarks are in order. As for the other cases, supply-side substitution is likely to be small owing to the low penetration of non-crude substitutes for jet fuel. However, demand for air transportation is complicated by the demand for transportation more broadly, which includes passenger vehicles as a possible mode. Air travel demand is generally more elastic relative to other modes, since most people do not use air transport to go to work or run errands (Dargay and Gately, 2010). What we are abstracting from in this case is the equilibrium adjustment in transportation mode choice as the RFS makes air transportation relatively more attractive relative to automotive transport. Computing the net impact on emissions from such switching is complicated, since it requires assumptions regarding the extent of substitution between modes for various classes of trips, and is contingent upon occupancy rate. Estimates of emissions per mile traveled from automobiles, however, do not differ considerably from emissions from airplanes, and so such equilibrium changes in transport mode are not likely to have considerable first order impacts on emissions (http://www.buses.org/files/ComparativeEnergy.pdf). Since we ignore emissions from this category we again are being conservative since such emissions from these demand-side adjustments for jet fuel are likely to imply additional emissions.

[30] The IPCC methods also consider N inputs from organic fertilizer and sewer sludge. In the US, nitrogen inputs, and therefore N_2O emissions, from organic fertilizer and sewer sludge are small and are therefore not considered (EPA, 2009).

crop residues are calculated using the crop yields from the economic model and crop-specific IPCC default parameters (IPCC, 2006).

Using the IPCC methods, the production of corn is more than twice as emissions intensive than each of the other crops and six times more emissions intensive than soybeans. Although the quantity of nitrogen additions is a major factor in quantifying N_2O emissions from agricultural production, other factors such as soil characteristics, previous crop, cropping practices and weather patterns can have a significant effect. As such, there is no agreed upon method for translating nitrogen additions to N_2O emissions.[31] To account for these uncertainties, as sensitivity analysis we adjust the agricultural emissions factors to reflect alternative methods for assessing N_2O emissions from agricultural production. For our low case, we use crop-specific N_2O emissions factors consistent with the US average of DAYCENT/CENTURY simulations used by the EPA (2010b). Relative to the central case, emissions from soybean production are three times greater in low agricultural N_2O case.[32] In the high case, we use the upper bound recommendation of Crutzen et al. (2008) and assume 5% of nitrogen in nitrogenous fertilizer is converted to N_2O.

Emissions from agricultural energy use are calculated using the crop specific energy input requirements from our agricultural data set and lifecycle emissions factors for the agricultural use of each energy type estimated using GREET 1.8c (Wang, 2009). These factors include both emissions from the combustion of the fossil fuel plus the emissions from the production and transportation of the fuel. Emissions from lime application to agricultural soils (0.12 kgCO2e/kg lime) are estimated using IPCC default methods which assume that all carbon in lime applied to agricultural soils is converted CO_2 (IPCC, 2006). We note that it has been suggested that the IPCC default emissions factors may be too high for the US Corn Belt as a portion of the limestone is leached from the field, preventing the carbon from being released (West and McBride, 2005).

We use GREET 1.8c (Wang, 2009) to estimate the emissions resulting from the production of nitrogenous (N), phosphate (P), and potassium (K) fertilizers, pesticide and agricultural lime. These estimates aggregate emissions from feedstock recovery and transportation, and the production and transportation of the final farm input.

The emissions from nitrogen production are 2.99 kgCO_2e per kilogram nutrient N. This factor is estimated assuming a US average nitrogen fertilizer mix of 70.7% ammonia, 21.1% urea and 8.2% ammonium nitrate,

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[31] For example, Crutzen et al. (2008) suggest that between 3-5% of the N in nitrogen additions to soil would be released as N_2O rather than the IPCC default of 1%. Crutzen et al. also find that total N_2O emissions calculated using the IPCC methods are consistent with their own analysis if all sources of N_2O emissions are considered, particularly livestock production and grazing.

[32] We refer to this as our low sensitivity case because it results in the RFS having a smaller net impact on agricultural emissions. This is primarily due to the increased emissions savings due to displaced soybean production. N_2O emissions from soybeans are substantially higher in the low emissions case because the DAYCENT/CENTURY models account for the nitrogen fixed by leguminous plants (soybeans).

which is based on USDA data. This emissions factor includes the emissions from producing the feedstock to fertilizer production (primarily natural gas) as well as the emissions from the production and transportation of the fertilizer itself. We use an emissions factor for the production of phosphate fertilizer of 1.04 $kgCO_2e$ per kg nutrient P. This factor includes the production, processing and transportation of sulfuric acid, phosphoric rock and phosphoric acid. Our emissions factor for the production of potassium fertilizer, which includes only the emissions from production and transportation of potassium oxide (K_2O), is 0.69 $kgCO_2e$/kg nutrient K. The lifecycle emissions of agricultural lime production are 0.63 $kgCO_2e$/kg lime and present the net emissions from mining, production and transportation. The emissions factor for the production of pesticide, 21.9 $kgCO_2e$/kg pesticide, represents the weighted average emissions from the production of four herbicides and a general insecticide.[33] The production of each N fertilizer material has different emissions intensity. In 2003, the emissions factors calculated by GREET for a kilogram of ammonia, urea, and ammonium nitrate are 2.62, 1.61 and 9.74 kgCO2e per kilogram N respectively (Wang, 2009). We assume that the shares of N fertilizer used by US agriculture are fixed over time.

Domestic Land Use Change We assume that the emissions from converting land held in CRP to cropland, $\phi_{N,D}$, are 2.3 $mgCO_2e$/ha. To calculate this factor we assume, following the EPA (2010b), that the conversion of CRP land to cropland results in the immediate release of all carbon stored in the above-ground biomass on CRP land. In addition, the carbon stored in below-ground biomass and soils of CRP land is released within the next 30 years. Consistent with standard practice (see EPA (2010b)), we amortize total emissions from land use conversion over 30 years, with no discounting.[34] We assume that CRP land is abandoned cropland planted to perennial grasses for 15 years (prior to conversion), having stored 30.51 $mgCO_2e$/ha in above and below ground biomass and 37.95 $mgCO_2e$/ha in soils (Fargione et al., 2008). We focus on the conversion of grasslands to cropland because while biomass on CRP land can take a number of different forms, in 2007 at least 77% of continuous signup CPR was classified as native or introduced grasses (FSA). Also, given the costs of converting forested land to cropland, it is CRP held in grassland that will likely be converted to cropland. If CRP lands converted to production sustained another type of land cover, for example native grasses or woody biomass, then the emissions consequences of conversion could be markedly higher (Fargione et al., 2008). On the other hand, the CRP targets marginal cropland with specific environmental benefits. If the land in CRP frequently moved in and out of agricultural production, or is degraded, the soils may have accumulated little soil carbon, and the emissions from converting the land

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[33] Crop specific shares of herbicide and insecticide to total pesticide are calculated from the ARMS. For each crop, the share of herbicide is greater than 90%. We use the GREET 1.8c assumptions for the herbicide mix applied to corn and soybeans, and assume herbicide applied to hay, wheat and cotton consists of equal parts of the four herbicides.

[34] The 30 year time frame is justified because this represents the average lifespan of an ethanol production facility. However, other studies have relied on different amortization assumptions. For example, Searchinger et al. (2008) use a 15 year time period.

back to cropland would be lower than our central estimate. To account for this uncertainty, we consider as sensitivity analysis the 95% confidence interval bounds for $\phi_{N,D}$ calculated with the standard deviation in total emissions released due to the conversion of abandoned cropland (24 mgCO$_2$e/ha) from Fargione et al. (2008).

World Land Use Change As a central value, we assume that the emissions benefits lost as a result of the expansion of non-US cropland, $\phi_{N,W}$, are 8.0 mgCO$_2$e/ha (EPA, 2010b). The emissions from world land use change are substantially larger than the emissions from domestic land use change. This is because cropland expansion in the rest of the world is predicted to displace previously undisturbed land cover with large carbon stocks. The international land use change emissions factors are derived from economic models used by the US EPA that predict the location (54 regions) and type (pasture, native ecosystems) of land converted to cropland as a result of the RFS for corn ethanol (EPA, 2010b).[35] The economic results are further disaggregated spatially and into twelve land conversion categories, including forest, grassland, shrubland and savanna among others. Land use conversion patterns are estimated using historical satellite land use cover data. There is considerable heterogeneity in the greenhouse gas emissions consequences of converting different native ecosystems to cropland because of the variability in carbon stored by different ecosystem types. For example, tropical forests, on average, have larger carbon stocks than temperate forests or grasslands, and as a result, tropical deforestation releases relatively more greenhouse gases than the conversion of temperate forests or grasslands. Due to the diversity in the types of land that could be converted to agricultural production in the rest of the world and the uncertainty in predicting where this conversion may take place, as sensitivity analysis we consider the 95% confidence bounds on $\phi_{N,W}$ reported in the EPA (2010b).

Supplementary Text

Details of Policy Context

The implied RFS for conventional biofuels requires that biofuels achieve 20% lifecyle emissions savings. It expands from 321 billion MJ in 2006 to 1,206 billion MJ in 2015 as is constant thereafter (US Congress, 2007). We assume that corn ethanol fills this entire mandate, which is consistent with the findings of the (EPA, 2010b).

The remaining volumes of the RFS are met by the RFS for advanced biofuels. The RFS for advanced biofuels expands from 48.9 billion MJ in 2009 to 1,690 billion MJ in 2022, hitting 442.2 billion MJ in 2015.

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[35] The EPA assessment of the RFS (EPA, 2010b) also allows for cropland to expand onto pasture land. To the extent that the amount of land held as pasture falls in response to biofuel policy (due to reduced livestock production), this pathway of adjustment serves to mitigate the conversion of native ecosystems to agriculture, and therefore greenhouse gas emissions.

Although the quantities mandated by the RFS for advanced biofuels are large by 2015, we abstract from the RFS for advanced biofuels because the technologies used to meet this mandate are produced only at small volumes and face considerable limits on their expansion in this time frame.

The three major biofuel technologies that will meet the RFS for advanced biofuels: biomass-based diesel, cellulosic ethanol, and imported sugarcane based ethanol. Biomass based diesel currently holds the largest market share of these three technologies in the US. However, the total quantity of biomass based diesel produced is small in relation to corn ethanol production and total US transportation fuel use. Cellulosic ethanol has been produced only at very small quantities. A portion of the RFS for advanced biofuels must be filled by cellulosic ethanol based on the RFS for cellulosic biofuels. Through 2012, however, the RFS for cellulosic biofuels has been scaled down each year because the EPA deemed the production capacity required to meet the mandate did not exist.[36] The EPA's unwillingness to keep the RFS for cellulosic ethanol at established levels illustrates the lack of cellulosic production capacity in the US. Expanded sugarcane ethanol imports, which would predominately come from Brazil and Caribbean Basin Initiative countries, face a variety of constraints in the short run EPA (2010b), including: non-tariff trade barriers, limits to the expansion of production capacity in Brazil, and limits in dehydration capacity that is required to make Brazilian ethanol compatible with the US market. For these reasons, the EPA finds only a small role for sugar cane ethanol imports by 2022, accounting for only 8.4 billion liters of the 79.4 billion liter advanced RFS by 2022 EPA (2010b).

In the unlikely scenario that the other mandates for the RFS are enforced and bind before 2015, then our estimates of the emissions savings of the RFS for corn ethanol will be biased. However, this bias will not affect the conclusions of our analysis because we are comparing emissions savings of policies and of LCA metrics calculated in the same hypothetical policy setting. Our lifecycle emissions savings measures could therefore be interpreted as the impact of the RFS for conventional biofuels and the VEETC conditional on the RFS for advanced biofuels never being enacted.

Technology-Based LCA estimates

Attributional LCA Estimates To construct attributional LCA estimates of emissions savings, we compare the per MJ lifecycle emissions of gasoline to the lifecycle emissions of a MJ of ethanol. The lifecycle emissions of ethanol are calculated by adding the emissions from the production of a MJ of ethanol to the

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[36] The text in the Energy Independence and Security Act of 2007 that gives the EPA the authority to lower the volumes required by the RFS is: "For any calendar year for which the projected volume of cellulosic biofuel production is less than the minimum applicable volume established under paragraph (2)(B), ... the Administrator shall reduce the applicable volume of cellulosic biofuel required under paragraph (2)(B) to the projected volume available during that calendar year. For any calendar year in which the Administrator makes such a reduction, the Administrator may also reduce the applicable volume of renewable fuel and advanced biofuels requirement established under paragraph (2)(B) by the same or a lesser volume" US Congress (2007).

emissions from the corn used to produce a MJ of ethanol less a co-product credit. The emissions from the corn used in ethanol production equals the amount of land used required to produce a MJ of ethanol, which depends on corn yields, times the emissions factor for corn production. The co-product credit accounts for animal feeds that are generated in the production of ethanol which can substitute for grains in the rations of livestock. The co-product credit accounts for the plausible reduction in demand for, and emissions from, grain production. These calculations include relevant upstream emissions, see discussion of emissions factors.

Our estimates of lifecycle emissions savings using attributional LCA are roughly 40 gCO_2e/MJ for each of the policy cases, with the variation driven by differences in baseline corn yields (Table SI.6). These estimates of emissions savings, and the contributions of each sector to the net change in emissions are consistent with other attributional studies (Liska et al., 2009; Wang et al., 2007). In the attributional framework, per MJ ethanol emissions from ethanol production are added to the emissions from producing the corn used in the production of a MJ of ethanol. From this total, a credit for the co-products of ethanol production, which can replace feedgrains in livestock rations, is deducted. Attributional LCA estimates modest emissions savings because emissions from market adjustments induced by expansions in ethanol are ignored.

Technology-Based Consequential LCA Estimates To construct technology-based consequential estimates for each policy, we subtract the agricultural, land use and ethanol production emissions of policy-based consequential estimates (per MJ ethanol) from the lifecycle emissions of a MJ of gasoline. This calculation effectively replicates the procedure used by EPA (2010b) within our modeling framework. Because each policy has a slightly different impact on the agricultural and land markets, per MJ ethanol, the technology-based consequential LCA estimates vary slightly across policy. Agricultural and land use emissions are more severe for policies that drive a larger increase in ethanol and that are evaluated from baselines with larger quantities of ethanol.

The EPA (2010b) analysis of the RFS in 2022, found that the lifecycle emissions of corn ethanol are 73.5 gCO_2e/MJ. This estimate established corn ethanol's compliance with the lifecycle emissions savings threshold of the RFS for conventional biofuels. Our model predicts that the technology-based consequential lifecycle emissions of corn ethanol are 87.1 gCO_2e/MJ in 2015 (Table SI.7). The EPA's analysis accounts for a number of minor emissions sources not captured by our model.[37] These sources' net contribution to the lifecycle emissions of ethanol is 8.0 gCO_2e/MJ. Our estimate of the technology-based consequential lifecycle emissions of ethanol is 33% higher than the EPA's estimate after deducting the emissions sources that are not common across the two estimates.

The differences between our emissions estimates and those of the EPA (2010b) are partially due to our

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[37] The seven sources are: domestic soil carbon, domestic and world livestock, domestic and world rice methane, and international farm inputs and N_2O.

reliance on a simpler agriculture and land use modeling framework. We chose this framework because our priority was integrating the fuel and agricultural markets into a single framework, rather than a detailed model of a single sector. For example, roughly one-third of the difference between our estimate and the EPA's estimate is due to our overestimation of emissions from rest of world land use change by 6.9 gCO_2e/MJ relative to the EPA (2010b). About a quarter of the difference is caused by our use of the IPCC 2006 methods and default emissions factors to estimate N_2O emissions from agricultural production as opposed to the EPA's use of more sophisticated biogeochemical models. A more detailed agricultural and land use framework would improve the precision of our estimates. However, our conclusions, which are made by comparing estimates across policies and across LCA metrics calculated within the same framework, are unlikely to be affected.

The remaining differences between our estimates and the EPA (2010b), likely arise from the various changes in policy and economic landscape between 2015 and 2022, combined with the scope of or agricultural model. First, the EPA (2010b) estimate will reflect trend improvements in crop yields and ethanol production technology. Second, the EPA (2010b) estimates that by 2022 biofuels meeting the RFS for advanced biofuels will be produced, at low levels, in absence of the RFS. As a result, the baseline land allocation will include biofuel feedstocks, in particular switchgrass, in addition to corn and food crops. The presence of additional feedstocks will put additional pressure on cropland that will not be present in 2015. While our primary agricultural land use adjustments are consistent with those of the EPA (2010b), that study predicts reductions in crops that are not included in our model. Per MJ additional ethanol, our predicted changes in corn, soybeans and wheat are consistent with the EPA (2010b). However, we find reasonably strong reductions in both hay and cotton while the EPA reports increases in hay and cotton, but reductions in switchgrass, sorghum, and various other minor crops.

Estimates for additional years

Table SI.8 displays the difference between policy-based and technology-based lifecycle savings estimates for each policy case in the years 2011, 2013 and 2015. This table illustrates two points. First, the large differences between policy-based and technology-based lifecycle emissions savings estimates are present across all years. This is illustrated by the larger and consistent differences in estimated emissions savings for the RFS compared to the VEETC baseline when the VEETC is renewed, and the RFS and VEETC when compared to the no-policy baseline.

Second, in contrast to technology-based methods, policy-based emissions savings can change dramatically as more ethanol is added to the economy by the policy. For the RFS when the VEETC is phased out, the policy-based emissions savings declines substantially as more ethanol is added to the economy, while the technology-based estimates of emissions savings remain relatively constant (Table SI.6). Thus, the difference between the policy-based and technology-based estimates of emissions savings can change dramatically as the policy causes larger increases in ethanol over time. In 2011, for a 96 billion MJ increase in ethanol, policy-based emissions savings are 12.7 gCO_2e/MJ greater than attributional emissions savings. In 2015, when the RFS increases ethanol by 236 billion MJ, the policy-based emissions savings are 29.8 gCO_2e/MJ less than the attributional emissions savings. Likewise, policy-based consequential emissions savings are 40.4 gCO_2e/MJ and 4.8 gCO_2e/MJ greater than the technology-based consequential lifecycle emissions savings in 2011 and 2015 respectively. The policy-based emissions savings decline as more ethanol is added by the RFS because of the positive impact of removing the VEETC on the price of blended fuel is fixed over time and therefore erodes as more ethanol is added by the RFS.

Sensitivity analysis

Figure SI.1 displays technology-based and policy-based lifecycle emissions savings metrics for each policy, under a range of parameter assumptions. The difference between technology-based and policy-based lifecycle emissions savings are reported in Table SI.9. We vary sets of parameters that account for uncertainties in two areas: 1) agricultural and land use emissions; and 2) the responsiveness of crude oil supply and demand in the rest of the world. Overall, this sensitivity analysis confirms that the large difference between policy-based and technology-based estimates of lifecycle emissions savings are robust to a broad range of parameter assumptions.

The second column in Table SI.9 reports our central results. The third and fourth columns present results for low and high cases for agricultural and land use emissions. For these cases we vary the crop production and land use emissions factors (see Table SI.15) and the ratios at which reduced US crop exports lead to land use change in the rest of the world. We find that the higher emissions factor cases lower the policy-based estimates of emissions savings for each policy. Thus, the difference between the policy-based and attributional estimates of emissions savings become greater, because emissions from land use change, which are not captured by attributional LCA, become larger. As the policy-based and technology-based consequential estimates account for agricultural and land use emissions in the same manner, the difference between these two estimates do not change across agricultural and land use emissions cases.

The next two columns present results under low and high values for the elasticity of crude oil supply. As the crude oil supply elasticity becomes larger, the differences between the policy-based and technology-based emissions savings estimates become smaller, but are still considerable. For higher elasticities, the reduction in the price of crude oil, and therefore gasoline, per unit of ethanol added by the policy is smaller. This causes the price of blended fuel to fall less drastically, or increase more drastically, so each policy displaces more gasoline per unit ethanol added, generating larger emissions reductions from gasoline displaced. This effect is offset slightly by increased emissions from rest-of-world crude oil, because higher elasticities of crude oil supply correspond to higher elasticities of world crude oil demand.

The final two columns in Table SI.9 report the combination of parameter assumptions that generate upper and lower bounds for policy-based lifecycle emissions savings. Even in these extreme cases, the technology-based methods are markedly different than the policy-based estimates.

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Table SI.1: Effects of Ethanol Policies on Ethanol (billion MJ)

	Baseline	Additional
VEETC Baseline		
RFS, VEETC Renewed		
2011	917.3	96.4
2013	958.0	152.4
2015	971.3	236.4
RFS, VEETC Phased Out		
2011	917.3	91.2
2013	958.0	146.4
2015	971.3	229.7
No-Policy Baseline		
RFS		
2011	439.2	580.8
2013	453.9	663.4
2015	556.0	657.0
VEETC		
2011	439.2	490.0
2013	453.9	488.1
2015	556.0	406.0

Table SI.2: Effects of Ethanol Policies on Crop Prices

	Baseline Price ($/Metric Ton)				Change (% per billion MJ ethanol)			
	Corn	Soybeans	Hay	Wheat	Corn	Soybeans	Hay	Wheat
VEETC Baseline								
RFS, VEETC Renewed								
2011	125.9	300.3	124.0	159.3	0.08%	0.01%	0.02%	0.04%
2013	128.2	304.6	133.1	160.4	0.10%	0.01%	0.04%	0.06%
2015	137.7	332.1	194.6	133.8	0.10%	0.01%	0.04%	0.08%
RFS, VEETC Phased Out								
2011	125.9	300.3	124.0	159.3	0.08%	0.01%	0.03%	0.04%
2013	128.2	304.6	133.1	160.4	0.11%	0.01%	0.05%	0.06%
2015	137.7	332.1	194.6	133.8	0.10%	0.01%	0.04%	0.09%
No-Policy Baseline								
RFS								
2011	89.9	277.6	107.0	143.9	0.09%	0.02%	0.03%	0.03%
2013	88.1	280.4	114.3	146.7	0.10%	0.01%	0.04%	0.03%
2015	92.8	309.9	174.2	131.7	0.13%	0.02%	0.03%	0.03%
VEETC								
2011	89.9	277.6	107.0	143.9	0.08%	0.01%	0.03%	0.03%
2013	88.1	280.4	114.3	146.7	0.10%	0.01%	0.03%	0.03%
2015	92.8	309.9	174.2	131.7	0.12%	0.01%	0.03%	0.03%

Table SI.3: Effects of Ethanol Policies on Land Use

	Baseline (million ha)			Change (ha per million MJ ethanol)			
	Corn	Other Crops	CRP	Corn	Other Crops	CRP	ROW Cropland
VEETC Baseline							
RFS, VEETC Renewed							
2011	33.9	79.7	12.6	7.0	-5.3	-1.7	3.6
2013	33.9	79.8	12.6	9.2	-6.8	-2.4	4.3
2015	33.4	80.2	12.6	8.1	-5.9	-2.2	4.7
RFS, VEETC Phased Out							
2011	33.9	79.7	12.6	7.0	-5.3	-1.7	3.6
2013	33.9	79.8	12.6	9.2	-6.8	-2.4	4.3
2015	33.4	80.2	12.6	8.1	-5.9	-2.2	4.7
No-Policy Baseline							
RFS							
2011	30.4	82.3	13.6	7.3	-5.4	-1.9	3.6
2013	30.4	82.5	13.4	7.4	-5.7	-1.7	3.7
2015	31.2	82.1	13.0	6.3	-5.1	-1.3	4.1
VEETC							
2011	30.4	82.3	13.6	7.1	-5.3	-1.8	3.6
2013	30.4	82.5	13.4	7.1	-5.5	-1.5	3.7
2015	31.2	82.1	13.0	5.3	-4.4	-0.9	4.3

Notes: Other crops include soybeans, wheat, hay and cotton.

Table SI.4: Effects of Ethanol Policies on Fuel Prices

	Baseline				Change (% per billion MJ ethanol)			
	Blended Fuel ($/1000 MJ)	Ethanol ($/1000 MJ)	Gasoline ($/1000 MJ)	Crude Oil ($/liter)	Blended Fuel	Ethanol	Gasoline	Crude Oil
VEETC Baseline								
RFS, VEETC Renewed								
2011	12.87	13.37	12.83	0.44	-0.004%	0.064%	-0.009%	-0.012%
2013	13.26	13.57	13.24	0.45	-0.002%	0.085%	-0.010%	-0.012%
2015	14.39	14.61	14.38	0.50	-0.002%	0.084%	-0.010%	-0.012%
RFS, VEETC Phased Out								
2011	12.87	13.37	12.83	0.44	0.020%	0.523%	-0.018%	-0.023%
2013	13.26	13.57	13.24	0.45	0.013%	0.368%	-0.015%	-0.020%
2015	14.39	14.61	14.38	0.50	0.008%	0.251%	-0.014%	-0.017%
No-Policy Baseline								
RFS								
2011	13.39	13.93	13.37	0.46	-0.004%	0.049%	-0.009%	-0.011%
2013	13.84	14.17	13.83	0.48	-0.004%	0.056%	-0.009%	-0.011%
2015	14.94	15.17	14.93	0.53	-0.003%	0.068%	-0.009%	-0.012%
VEETC								
2011	13.39	13.93	13.37	0.46	-0.007%	-0.008%	-0.008%	-0.010%
2013	13.84	14.17	13.83	0.48	-0.007%	-0.008%	-0.008%	-0.010%
2015	14.94	15.17	14.93	0.53	-0.007%	-0.008%	-0.008%	-0.009%

Notes: Price of ethanol includes VEETC.

Table SI.5: Effects of Ethanol Policies on Fuel Quantities

	Baseline		Change per billion MJ ethanol	
	Gasoline (billion MJ)	ROW Crude Oil (billion liters)	Gasoline (billion MJ)	ROW Crude Oil (billion liters)
VEETC Baseline				
RFS, VEETC Renewed				
2011	14210.0	2111.5	-0.87	0.005
2013	14330.1	2165.3	-0.90	0.005
2015	14262.8	2219.1	-0.90	0.005
RFS, VEETC Phased Out				
2011	14210.0	2111.5	-1.71	0.010
2013	14330.1	2165.3	-1.46	0.009
2015	14262.8	2219.1	-1.26	0.008
No-Policy Baseline				
RFS				
2011	14529.9	2109.1	-0.85	0.005
2013	14655.0	2162.7	-0.86	0.005
2015	14509.7	2216.7	-0.87	0.005
VEETC				
2011	14529.9	2109.1	-0.74	0.004
2013	14655.0	2162.7	-0.72	0.004
2015	14509.7	2216.7	-0.70	0.004

Notes: World crude oil reported here includes only the components of the world crude oil market from which we calculate emissions from: crude oil used to produce gasoline in the rest of the world, and crude oil used to produced distillate fuels in the US and the rest of the world.

Table SI.6: Technology-based Lifecycle Emissions Savings (gCO_2e/MJ)

	Attributional	Consequential
VEETC Baseline		
RFS, VEETC Renewed		
2011	38.7	17.6
2013	39.3	6.5
2015	40.0	5.9
RFS, VEETC Phased Out		
2011	38.7	17.3
2013	39.3	5.8
2015	40.0	5.4
No-Policy Baseline		
RFS		
2011	39.9	15.7
2013	40.5	15.9
2015	41.0	16.3
VEETC		
2011	39.9	16.8
2013	40.5	17.0
2015	41.0	17.9

Table SI.7: Policy-based Lifecycle Emissions Savings (gCO_2e/MJ), Decomposed by Emissions Source

	Ethanol						Gasoline Savings		
	Total	Ethanol Production	Corn Production	Other Crops	CRP Conversion	World Land Use Change	Total	Gasoline Displaced	Crude Oil
VEETC Baseline									
RFS, VEETC Renewed									
2011	75.4	27.3	20.7	-5.1	3.9	28.6	68.0	81.0	-13.0
2013	86.6	27.3	26.0	-6.2	5.4	34.1	70.2	83.9	-13.7
2015	87.1	27.3	23.4	-5.8	5.0	37.3	69.6	83.6	-14.1
RFS, VEETC Phased Out									
2011	75.8	27.3	20.7	-5.1	3.9	29.1	133.4	158.9	-25.5
2013	87.3	27.3	26.2	-6.2	5.4	34.6	113.9	136.0	-22.2
2015	87.7	27.3	23.4	-5.8	5.0	37.7	97.8	117.5	-19.7
No-Policy Baseline									
RFS									
2011	77.4	27.3	21.6	-4.9	4.4	28.9	66.9	79.2	-12.3
2013	77.2	27.3	21.6	-5.0	4.0	29.3	67.1	79.6	-12.5
2015	76.8	27.3	18.3	-4.4	2.9	32.7	68.0	81.2	-13.2
VEETC									
2011	76.3	27.3	21.0	-4.8	4.2	28.5	58.3	69.1	-10.8
2013	76.0	27.3	20.6	-4.9	3.5	29.4	56.7	67.3	-10.7
2015	75.1	27.3	14.9	-3.5	2.0	34.4	54.4	65.2	-10.7

Table SI.8: Difference Between Technology-based and Policy-based Metrics (gCO_2e/MJ)

		Difference from Policy-based	
	Policy-based	Attributional	Technology-based Consequential
VEETC Baseline			
RFS, VEETC Renewed			
2011	-7.5	46.2	25.1
2013	-16.4	55.6	22.8
2015	-17.5	57.5	23.5
RFS, VEETC Phased Out			
2011	57.6	-18.9	-40.4
2013	26.6	12.7	-20.8
2015	10.2	29.8	-4.8
No-Policy Baseline			
RFS			
2011	-10.5	50.4	26.2
2013	-10.1	50.6	26.0
2015	-8.8	49.8	25.1
VEETC			
2011	-17.9	57.9	34.7
2013	-19.4	59.9	36.4
2015	-20.7	61.7	38.6

Table SI.9: Sensitivity of Lifecycle Emissions Savings, 2015

Emissions Factors Crude Oil Elasticity	Central Central	Low Central	High Central	Central Low	Central High	Low High	High Low
VEETC Baseline; RFS, VEETC Renewed							
Baseline Ethanol (billion MJ)	971.3	971.3	971.3	1001.5	955.3	955.3	1001.5
Change in Ethanol	236.4	236.4	236.4	209.1	250.7	250.7	209.1
Policy Based (gCO_2e/MJ)	-17.5	5.3	-61.3	-34.0	-9.8	12.8	-79.4
Ethanol	87.1	64.3	130.9	88.9	86.4	63.8	134.3
Gasoline	69.6	69.6	69.6	54.8	76.6	76.6	54.8
Difference from Policy-based (gCO_2e/MJ)							
Attributional	57.5	37.2	81.4	73.9	49.8	29.7	99.3
Tech-based Consequential	23.5	23.5	23.5	38.2	16.5	16.5	38.2
VEETC Baseline; RFS, VEETC Removed							
Baseline Ethanol (billion MJ)	971.3	971.3	971.3	1001.5	955.3	955.3	1001.5
Change in Ethanol	229.7	229.7	229.7	203.7	243.4	243.4	203.7
Policy Based (gCO_2e/MJ)	10.2	33.2	-34.0	-9.3	19.0	41.7	-55.1
Ethanol	87.6	64.6	131.8	89.4	86.9	64.1	135.2
Gasoline	97.8	97.8	97.8	80.1	105.8	105.8	80.1
Difference from Policy-based (gCO_2e/MJ)							
Attributional	29.8	9.2	54.1	49.2	21.1	0.8	75.0
Tech-based Consequential	-4.8	-4.8	-4.8	13.0	-12.8	-12.8	13.0
No Policy Baseline; RFS							
Baseline Ethanol (billion MJ)	556.0	556.0	556.0	641.0	511.8	511.8	641.0
Change in Ethanol	657.0	657.0	657.0	579.7	696.8	696.8	579.7
Policy Based (gCO_2e/MJ)	-8.8	10.5	-43.5	-23.8	-1.8	17.4	-59.4
Ethanol	76.8	57.5	111.5	77.8	76.3	57.1	113.5
Gasoline	68.0	68.0	68.0	54.0	74.5	74.5	54.0
Difference from Policy-based (gCO_2e/MJ)							
Attributional	49.8	33.0	65.6	64.6	42.8	26.2	81.2
Tech-based Consequential	25.1	25.1	25.1	39.0	18.6	18.6	39.0
No Policy Baseline; VEETC							
Baseline Ethanol (billion MJ)	556.0	556.0	556.0	641.0	511.8	511.8	641.0
Change in Ethanol	406.0	406.0	406.0	366.0	425.6	425.6	366.0
Policy Based (gCO_2e/MJ)	-20.7	-1.8	-53.9	-34.5	-14.0	4.7	-69.2
Ethanol	75.2	56.2	108.4	76.7	74.4	55.6	111.4
Gasoline	54.4	54.4	54.4	42.2	60.3	60.3	42.2
Difference from Policy-based (gCO_2e/MJ)							
Attributional	61.7	45.3	76.1	75.4	55.1	38.9	91.0
Tech-based Consequential	38.6	38.6	38.6	50.9	32.7	32.7	50.9

Notes: The elasticity of crude oil supply is set to 0.25 in the low case, 0.5 in the central case, and 0.75 in the high case. The corresponding elasticities of world crude oil demand are -0.01, -0.02 and -0.03 respectively. The emissions factor cases correspond to the emissions factors in table SI.15. In the low emissions factor case, world land use conversion ratios are set 20% lower than the central case. In the high emissions factor case, world land use conversion ratios are set 20% higher than the central case.

Table SI.10: Description of US Economy in Year of Calibration - 2003

	Value	Source
Total Size of Economy (billion \$)	\$7,667.60	NIPA
Net Government Expenditures (billion \$)	\$2,828.90	NIPA
After Tax Value of Labor (billion \$)	\$4,811.08	
Net Returns from Land Endowment (billion \$)	\$27.61	NASS, CRPS, CCR
US Land Endowment (million hectares)	112.68	
Corn	31.37	NASS
Soybeans	29.33	NASS
Wheat	21.47	NASS
Hay	25.65	NASS
Cotton	4.68	NASS
CRP	13.57	CRPS
Crop Yields (metric ton/hectare)		
Corn	8.9	NASS
Soybeans	2.6	NASS
Wheat	3.0	NASS
Hay	6.1	NASS
Cotton	0.8	NASS
Crop Prices (\$/metric ton)		
Corn	\$95.23	NASS
Soybeans	\$269.62	NASS
Hay	\$94.22	NASS
Wheat	\$118.65	NASS
Cotton	\$1,036.32	NASS
Fuel Quantities		
VMT (trillion passenger miles)	2.69	FHWA
Blended Fuel (billion MJ)	16,076.57	
Ethanol (billion MJ)	220.91	FHWA
Regular Gasoline (billion MJ)	15,855.66	FHWA
Domestic Crude Oil (billion barrels)	3.12	GCH, CSD, BNI
Rest of World Crude Oil (billion barrels)	23.07	IEA 2006
Fuel Prices		
VMT (\$/passenger mile)	\$0.19	
Blended Fuel (\$/1000 MJ)	\$7.07	
Ethanol (\$/1000 MJ)	\$9.98	
Regular Gasoline (\$/1000 MJ)	\$7.03	AER
Crude Oil (\$/liter)	\$0.18	AER
Labor Tax Rate (%)	36.59%	
CRP Rental Payment (\$/hectare)	\$114.48	CRPS
Price of Labor (\$/hour)	\$9.05	NASS

Notes: Entries with no source listed are imputed given other data and calibration assumptions. Ethanol price includes the VEETC.

Table SI.11: Key Calibration Parameter Values

Parameter	Value	Source
Households		
Elasticity of substitution, Household Utility, σ_U	0.5	
Elasticity of substitution, Household Utility, σ_T	0.09	
Expenditure Share on Food	0.035	
Expenditure Share on VMT	0.065	
Elasticity of substitution, VMT, σ_M	0.21	
Ratio of fuel cost to total cost of driving	0.4	
Initial Fuel Economy (km/liter)	8.7	FHWA
Ethanol		
kilograms corn required per liter ethanol, $\lambda_{E,Y}$	2.56	Wang (2009)
Labor expenditures per liter ethanol, $\lambda_{E,L}$	\$0.13	Farrell et al. (2006)
Average tariff rate (plus fuel surcharge) per liter of ethanol	\$0.02	
Regular Gasoline and Crude Oil		
Elasticity of substitution, Regular Gasoline Production, σ_G	0.06	
Share of per unit crude oil cost to total cost of gasoline	0.61	GCH, CSD, BNI
Elasticity of crude oil excess supply, η_R	0.50	
Other Markets		
Elasticity of substitution, Food Production, σ_X	0.08	
Elasticity of substitution, Food Production, σ_Q	0.3	
Elasticity of substitution, Food Production, σ_V	0.25	
Share of crop expenditures on food to total food expenditures	0.19	
Crop Export Markets		
Elasticity of ROW demand for US exports		Gardiner and Dixit (1987)
Corn	-0.65	
Soybean	-0.6	
Wheat	-0.55	
Cotton	-0.75	
Share of crop exports to total US Production		PSD
Corn	0.19	
Soybeans	0.36	
Wheat	0.49	
Cotton	1	

Notes: See text for acronym definitions. Values are reported for 2003. A subset of parameters are updated annually, see text for details.

Table SI.12: Agricultural Expenditure Dataset

Total Expenditures ($/hectare)

	Labor	Capital	Energy	Fertilizer	Total
Corn	73.32	142.06	57.06	386.97	659.41
Soybeans	44.50	108.33	21.67	209.92	384.43
Hay	49.08	130.13	27.06	153.26	359.52
Wheat	49.08	130.13	27.06	167.96	374.22
Cotton	124.39	157.14	60.27	749.58	1092.37

Components of Fertilizer Expenditure ($/hectare)

	N	P	K	Seed	Chemicals	Other
Corn	89.97	21.40	19.05	84.76	64.74	107.05
Soybeans	2.52	5.41	7.78	67.76	41.81	84.63
Hay	20.11	15.20	7.69	18.78	17.15	74.31
Wheat	43.89	11.27	2.59	18.78	17.15	74.31
Cotton	52.19	13.57	13.49	91.90	162.62	415.83

Table SI.13: Target Crop Elasticities Used for Estimation

	Corn Area	Soybean Area	Hay Area	Wheat Area	Cotton Area
Corn Price	0.29	-0.23	-0.05	-0.05	-0.07
Soybean Price	-0.15	0.27	-0.01	-0.01	-0.08
Hay Price	-0.07	-0.01	0.20	-0.08	-0.10
Wheat Price	-0.07	-0.01	-0.06	0.34	-0.06
Cotton Price	-0.03	-0.02	-0.08	-0.01	0.47

Notes: The elasticity of CRP land with respect to the marginal net returns to cropland is -0.07. The own price elasticity of hay area, the cross price elasticity of hay area with respect to the price of corn and the elasticity of corn area with respect to the price of hay represent an average of Arnade and Kelch (2007) and Orazem and Miranowski (1994). The elasticity of hay area with respect to the price soybeans, wheat and cotton, and the elasticity of wheat and cotton area with respect to the price of hay represent best guesses. All remaining values are from Lin et al. (2000).

Table SI.14: Calibration of Crude Oil Market

Crude Market Component	Quantity (billion liters)	Ratio with Crude for US Gasoline	Central Elasticity
Total World Crude Oil	4545.8	-	-
US Demand for Crude Oil for Gasoline	490.3	-	0.50
US Crude Oil Supply	499.6	1.0	0.045
ROW Crude Oil Supply	4046.2	8.3	0.035
ROW Crude Oil Demand	3419.5	7.0	-0.02
US Distillate Demand	225.0	0.5	-0.02
US Other Crude Products Demand	411.0	0.8	-0.02

Notes: The value for crude for US gasoline is the value used in our model. This value is slightly below the total quantity of crude for US gasoline reported by the EIA because we ignore US gasoline for non-transportation purposes in our model. The elasticity of crude for US gasoline is calculated following equation (20). All other elasticity values are from literature sources reported in the text. Our category of other crude products includes residual fuels, jet fuel, kerosene, LPG and EIA defined other petroleum products.

Table SI.15: Emissions Factors

	Central	Low	High	Source
Gasoline (gCO_2e/MJ)	93.0			
Combustion	75.1	-	-	EPA (2010b)
Production	18.9	-	-	EPA (2010b)
Ethanol (gCO_2e/MJ)	27.4			
Combustion	0.8	-	-	EPA (2010b)
Production	26.6	-	-	EPA (2010b)
Crude Oil ($kgCO_2e/liter$)	2.6	-	-	EPA (2011)
Agriculture ($MgCO_2e/ha/year$)				
Corn	3.2	2.9	5.6	
Soybeans	0.5	1.8	0.4	
Hay	1.3	1.3	2.5	
Wheat	1.0	1.6	1.3	
Cotton	1.4	1.6	2.9	
Land Use Emissions Benefits Lost Upon Conversion ($MgCO_2e/ha/year$)				
CRP	2.3	0.7	3.9	Fargione et al. (2008)
Rest of World	8.0	5.9	10.5	EPA (2010b)

Notes: See Appendix for description of calculations. N_2O emissions from agricultural production depend on crop yields and therefore vary slightly by year and policy. Values in baseline for 2003 are reported here. The emissions factor for crude oil is the average emissions from gasoline and distillates used outside the US, weighted by 2003 quantities of these products.

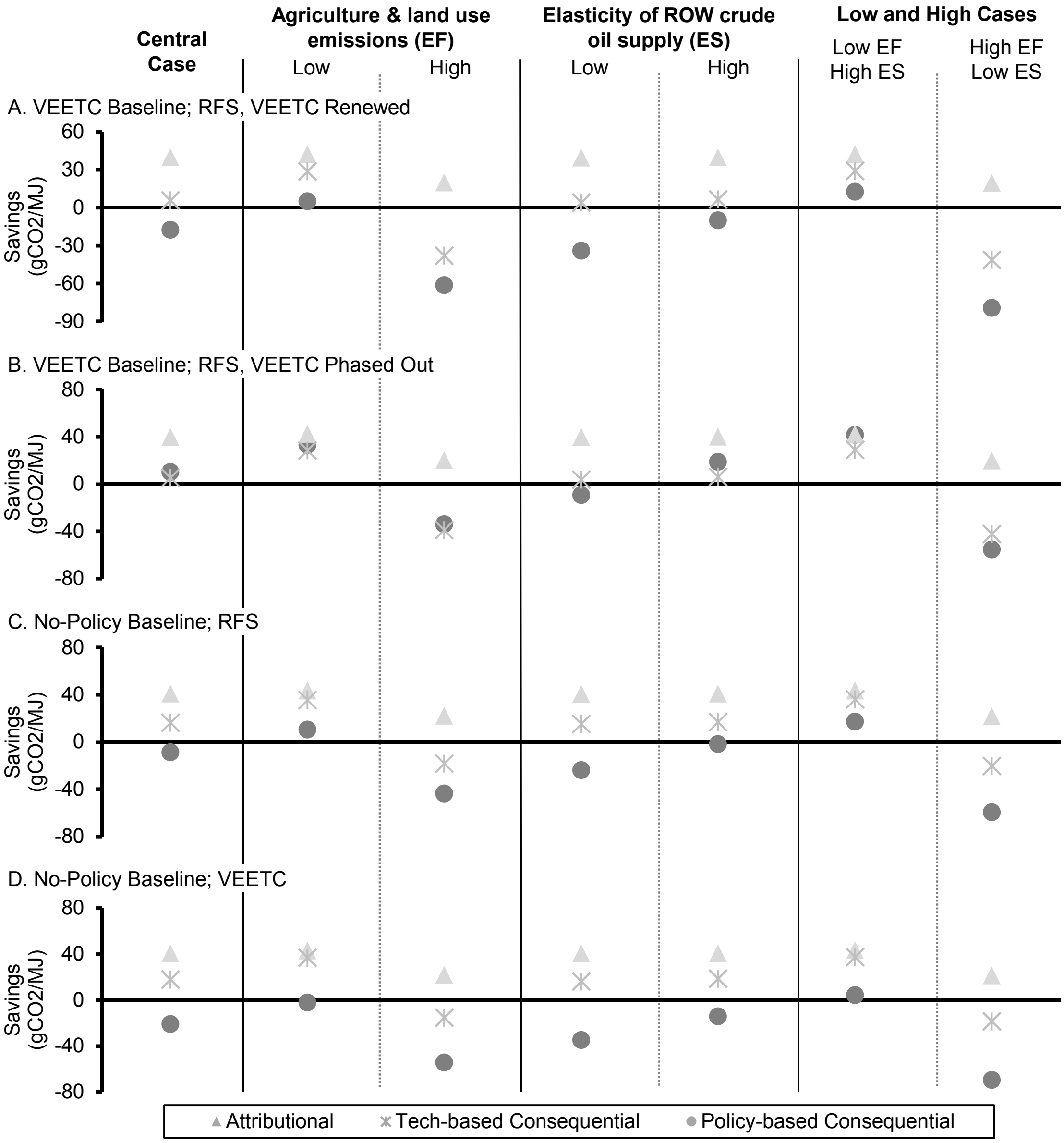

Figure SI.1: Sensitivity of Lifecycle Metrics to Parameter Assumptions