Appendix

Are there Carbon Savings from US Biofuel Policies? The Critical Importance of Accounting for Leakage in Land and Fuel Markets

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This appendix provides the intermediate steps in the derivation of the marginal emissions formula (Section I), a full exposition of the simulation model and additional results. In Section II we present the functional forms used in the simulation model and highlight the key differences between the analytic model and the simulation model. Section III discusses the parameter values and data sources used for calibration. Section IV outlines the assumptions and data sources which are the basis for our construction of marginal emissions factors. In Section V we outline the assumptions regarding the dynamic trends that underlie our simulation results. Section VII validates our baseline against historical data and compares our projections to the USDA's Long Term Projections. Section VIII presents additional sensitivity analysis not reported in the text. Finally, Section IX contains tabular results for the impact of the RFS on crop prices, intended emissions savings and leakage per liter of ethanol added by the RFS.

I. Derivation of Marginal Emissions Formula

To derive the marginal emissions formula, equation (19), we totally differentiate total emissions with respect to the RFS, θ:

$$\begin{aligned}\frac{dGHG}{d\theta} &= \phi_G \frac{dG}{d\theta} + \phi_E \frac{dE}{d\theta} + \phi_Y \frac{dA_Y}{d\theta} + \phi_Z \frac{dA_Z}{d\theta} \\ &+ \phi_{N,D} \frac{dA_{N,D}}{d\theta} + \phi_{N,W} \frac{dA_{N,W}}{d\theta} + \phi_R \frac{dR_W}{d\theta}\end{aligned} \tag{A.1}$$

where:

$$\frac{dG}{d\theta} = g_F \frac{dF}{d\theta} + F \frac{dg_F}{d\theta} \qquad \text{and} \qquad \frac{dE}{d\theta} = e_F \frac{dF}{d\theta} + F \frac{de_F}{d\theta}. \tag{A.2}$$

Adding the following terms to equation (A.1)

$$\begin{aligned}&\phi_G \left(\frac{dE}{d\theta} - \frac{dE}{d\theta} \right) \\ &\phi_Y \frac{dE}{d\theta} \left(\tilde{A}_Y - \tilde{A}_Y \right)\end{aligned} \tag{A.3}$$

recognizing that

$$\frac{dF}{d\theta} = \frac{dG}{d\theta} + \frac{dE}{d\theta} \tag{A.4}$$

and rearranging terms yields equation (19). The equations in (A.3) allow for the intended emissions savings and leakage. Equation (A.4) follows from the equations in (A.2).

II. Functional Forms

We use a numerical model with the same general structure as our analytical model to quantify each of the terms of equation (19) for the years 2009-2015. Here we lay out the key functional form assumptions of the numerical model.

Consumer

The representative agent is assumed to have preferences given by the following nested constant elasticity of substitution (CES) utility function:

$$\begin{aligned}U(F,X,C,H) &= \left[\alpha_U M(F,H)^{\frac{\sigma_U - 1}{\sigma_U}} + (1-\alpha_U) W(C,X)^{\frac{\sigma_U - 1}{\sigma_U}} \right]^{\frac{\sigma_U}{\sigma_U - 1}} \\ W(C,X) &= \gamma_W \left[\alpha_W C^{\frac{\sigma_W - 1}{\sigma_W}} + (1-\alpha_W) X^{\frac{\sigma_W - 1}{\sigma_W}} \right]^{\frac{\sigma_W}{\sigma_W - 1}} \\ M(F,H) &= \gamma_M \left[\alpha_M F^{\frac{\sigma_M - 1}{\sigma_M}} + (1-\alpha_M) H^{\frac{\sigma_M - 1}{\sigma_M}} \right]^{\frac{\sigma_M}{\sigma_M - 1}}\end{aligned} \tag{A.5}$$

where W is a composite of food and other consumption, M denotes vehicle miles traveled (VMT)[1] and H denotes fixed costs of driving. σ_U, σ_W, and σ_M are elasticities of substitution, $\alpha_U, \alpha_W, \alpha_M$ are share parameters, and γ_W and γ_M are scale parameters. Nesting utility in this way implies weak-separability between VMT and other consumption. In embedding the VMT decision we permit substitutability between fixed costs of driving and blended fuel allowing fuel economy to be endogenously determined.[2]

In the simulation model the terms-of-trade balance (value of crop exports sold less crude oil imports purchased) added to the consumers income. Formally, the value of the terms-of-trade balance, T is given by:

(A.6)
$$T = \int_{P_Y^0}^{P_Y^{RFS}} Y_{X,W}(P_Y, P_Z) dP_Y + \int_{P_Z^0}^{P_Z^{RFS}} Z_{X,W}(P_Y, P_Z) dP_Z - \int_{P_R^0}^{P_R^{RFS}} R_W(P_R) dP_R,$$

where the prices superscripted 0 are baseline prices and the prices superscripted RFS are prices when the RFS is imposed.

Land Use Allocation

The land owner's decision closely follows equation (11), except that we consider five crops, corn soybeans, wheat, hay and cotton, as well as land allocated to the CRP.[3] We assume that the yield (payment) functions in (11) is linear in the quantity of land allocated to each land use (A_i):

$$y_i(A_i) = \beta_i - \delta_i A_i \tag{A.7}$$

where β_i and δ_i are the intercept and exogenous slope coefficients of crop i's linear yield function.

Only corn is used to produce ethanol, while corn, soybeans, hay and wheat are all used in food production. Corn, soybeans, wheat and cotton are exported to the rest of the world.

[1]We use "miles" and "VMT" in the description here because it follows the literature. We report values in kilometers to maintain consistency in metric units throughout the paper.

[2]Our use of a CES functional form to model the trade-off between blended fuel and fixed costs of driving is commonly used by other simulation models in this area, see for example Parry and Small (2005). Importantly, this functional form permits price induced substitution from blended fuel to fixed costs of driving, in effect permitting an improvement in the average fuel economy of the vehicle fleet in response to fuel price changes, which has important implications for domestic fuel market leakage. Critically, this functional form allows one to distinguish the own price elasticity of blended fuel from the elasticity of VMT with respect to the price of blended fuel. As the econometric literature in this area has shown (see Bento et al. (2009); Small and Dender (2007)), these elasticities are not the same owing to the fact that consumers respond to increases in fuel prices by both altering fuel consumption but also their demand for fuel economy. Ignoring this important difference in VMT and blended fuel output response, by instead specifying consumption over blended fuel directly, would imply larger and unrealistic changes in domestic blended fuel markets and consequently domestic fuel market leakage.

[3]The subscript i in equation (11) now indexes six land uses.

Fuel blenders, equation (4) in the analytical model, are constrained by a linear production function:

$$F = \Gamma_F E + G \tag{A.8}$$

where Γ_F is set so that ethanol and gasoline are energy equivalent perfect substitutes. Our treatment of blended fuel production as energy equivalent perfect substitutes is similar to the approach taken by de Gorter and Just (2009) but contrasts with Khanna et al. (2008), who use a constant elasticity of substitution (CES) functional form for this sector. We believe such a functional form is overly restrictive given that the share parameters entering that function are not endogenous and instead fixed to calibration year data. Unlike de Gorter and Just (2009), however, we solve for the share of ethanol in the absence of the RFS, using the first-order conditions of the profit maximization problem when the RFS constraint is not present.

When the RFS is not binding or not present, the fuel blender's profit maximization problem implies:

$$\Gamma_F = \frac{P_E - \tau}{P_G}. \tag{A.9}$$

We can identify the share of ethanol in blended fuel, $\Theta = \frac{E}{F}$, such that the above condition holds. In this case the price of blended fuel in the baseline is given by: $P_F = (P_E - \tau)\,\Theta + P_G\,(1 - \Gamma_F \Theta) - t_F$, where t_F is a pre-existing fuel tax. In contrast, the price of blended fuel when the RFS is binding is given by: $P_F = (P_E - \tau)\,\theta + P_G\,(1 - \Gamma_F \theta) - t_F$, when the VEETC is renewed, and $P_F = P_E \theta + P_G\,(1 - \Gamma_F \theta) - t_F$, when the VEETC is allowed to expire.

When the VEETC is renewed, the change in the price of blended fuel due to the RFS is given by: $P_F^1 - P_F^0 = \theta P_E^1 - \Theta P_E^0 - \tau\,(\theta - \Theta) + (1 - \Gamma_F \theta)\,P_G^1 - (1 - \Gamma_F \Theta)\,P_G^0$, where superscripts denote post-policy (1) and baseline (0). However, when the VEETC is allowed to expire, the change in the price of blended fuel due to the RFS is given by: $P_F^1 - P_F^0 = \theta P_E^1 - \Theta P_E^0 + \tau\Theta + (1 - \Gamma_F \theta)\,P_G^1 - (1 - \Gamma_F \Theta)\,P_G^0$. Note that while, $\tau\,(\theta - \Theta)$ is very close to zero (the change in the share of ethanol in blended fuel, $\theta - \Theta$ is very small), $\tau\Theta$ is not, reflecting the fact that when the RFS is imposed the full change in the price of ethanol is now passed along to the consumer through the change in the price of blended fuel.

Ethanol is produced according to a Leontief production function:

$$E = \min\left\{\frac{Y_E}{\lambda_{E,Y}}, \frac{L_E}{\lambda_{E,L}}\right\} \tag{A.10}$$

where Y_E is corn used for ethanol production and L_E is expenditures on labor, and $\lambda_{E,Y}$ and $\lambda_{E,L}$ are exogenous parameters that determine much corn and labor are required to produce a unit of ethanol. Ethanol is actually a joint production process which produces, in addition to ethanol, 'co-products' which can be used in place of grains in livestock feeds. We consider four co-products, dried distillers grains, corn gluten meal, corn gluten feed, and corn oil which are used in food production.[4]

Gasoline production is modeled with a nested constant returns to scale CES technology:

$$G(R_G, L_G) = \gamma_G \left[\alpha_G R_G^{\frac{\sigma_G - 1}{\sigma_G}} + (1 - \alpha_G) L_G^{\frac{\sigma_G - 1}{\sigma_G}} \right]^{\frac{\sigma_G}{\sigma_G - 1}} \tag{A.11}$$

where α_G is a share parameter, γ_G, is a scale parameter, and σ_G is the elasticity of substitution.

World Crop Demand

The rest-of-world consumption of US agricultural products is specified according to inverse excess (or import) demand functions:

$$P_i = \gamma_i \left(Q_i^{\frac{1}{\eta_i}} \right) \tag{A.12}$$

where Q_i is the amount of crop i demanded (net of supply) by the rest of the world, γ_i is a scale parameter for the crop i demand function, and η_i is the rest-of-world excess demand elasticity for crop i. Here i corresponds to trade in agricultural products with respect to the rest of the world, that is i spans corn, soybeans, wheat, and cotton. Given changes in crop exports, we impute how cropland expands at the expense of non-agricultural land uses, A_N, in the rest-of-world economy.

World Crude Oil Supply

We consider a simple model of crude oil supply that abstracts from market power considerations with respect to the production and refinement of crude oil. We specify the inverse rest-of-world excess (or export) supply of crude oil as:

$$P_R = \gamma_R \left(R^{\frac{1}{\eta_R}} \right) \tag{A.13}$$

where R is the amount of crude oil (net of demand) supplied by the rest of the world, γ_R is a scale parameter, and η_R is the rest-of-world excess supply elasticity for crude oil.

[4] We assume that these four 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, which is endogenous, is taken as a rebate to the ethanol producer, and therefore subtracted from the marginal cost of producing ethanol.

Food Production

Food production is modeled as a set of nested constant returns to scale CES functions:

$$X(Y_i, L_X) = \gamma_X \left[\alpha_X L_X^{\frac{\sigma_X - 1}{\sigma_X}} + (1-\alpha_X)\, Q(Y_i)^{\frac{\sigma_X - 1}{\sigma_X}} \right]^{\frac{\sigma_X}{\sigma_X - 1}}$$

$$Q(Y_i) = \gamma_Q \left[\alpha_{Y_3} Y_3^{\frac{\sigma_Q - 1}{\sigma_Q}} + \alpha_{Y_4} Y_4^{\frac{\sigma_Q - 1}{\sigma_Q}} + (1-\alpha_{Y_3}-\alpha_{Y_4})\, V(Y_1, Y_2)^{\frac{\sigma_Q - 1}{\sigma_Q}} \right]^{\frac{\sigma_Q}{\sigma_Q - 1}}$$

(A.14)

$$V(Y_1, Y_2) = \gamma_V \left[\alpha_V Y_1^{\frac{\sigma_V - 1}{\sigma_V}} + (1-\alpha_V)\, Y_2^{\frac{\sigma_V - 1}{\sigma_V}} \right]^{\frac{\sigma_V}{\sigma_V - 1}}$$

where L_X is the amount of labor used in food production, Q is a composite feedstuffs index including the four food crops and co-products, V is a composite index including corn, soybeans and co-products, Y_i is the amount of crop i needed to produce food.[5] σ_X, σ_Q, and σ_V are elasticities of substitution, α_X, α_{Y3}, α_{Y4} and α_V are share parameters, and γ_X, γ_Q and γ_V are scale parameters. Here, Y_1 and Y_2 are corn and soybeans used by the food sector net of ethanol co-products.

III. Data and Calibration

Benchmark Economy

Table A.1 presents the characteristics of the US economy for the calibration year, 2003. 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 Economic Research Service (ERS) *Agricultural Resource Management Survey* (ARMS), is conducted for each major crop on a rotating quadrennial basis and 2003 is the central year of a recent four year cycle. In 2003, 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 representative agent's labor endowment. This implies an after-tax value of the labor endowment of \$4.8 trillion.[6] The net returns from land holdings comprise the remainder of GDP, \$27.6 billion, which is small in comparison to total GDP.

In 2003, 112.68 million hectares of cropland 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. In addition to cropland, 13.57 million hectares were held as CRP. This

[5] The crops are indexed as follows, corn ($i = 1$), soybeans ($i = 2$), hay ($i = 3$), and wheat ($i = 4$).

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

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 intentionally exclude those categories of CRP land which are not likely to be converted back into crop production, given the higher rental payments that are received or the services they provide, such as rare habitat conservation, riparian buffers, etc. The average CRP rental rate was $114.48 per hectare.[7] Crop prices represent national average prices (paid to the farmer) reported to the USDA's National Agricultural Statistics Service (NASS). Average yields in the US for corn, soybeans, hay, wheat and cotton are also from NASS.

Blended fuel consumption in 2003 was 499.97 billion liters, of this regular gasoline made up 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. Total ethanol consumption was 10.39 billion liters according to the US Federal Highway Administration's *Highway Statistics 2003* (FHWA). The price of regular gasoline, $0.23 per liter, is the consumption weighted US average spot price for all grades of conventional gasoline from the EIA's *Annual Energy Review 2008*. We compute a spot price for ethanol in 2003 of $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.[8] Given benchmark quantities and prices of gasoline and ethanol, the 2003 price of blended fuel is $0.41 per liter, inclusive of the VEETC.

Consumer

We specify elasticities of substitution between miles and non-mile expenditures, σ_U in (A.5), of 0.50, between food and the composite good, σ_W in (A.5), of 0.09, and between fuel and non-fuel expenditures on driving, σ_M in (A.5), of 0.21. We selected these in order to imply a calibrated own-price elasticity of demand for food of -0.12, an own-price elasticity of demand for blended fuel of -0.34, and a cross-price elasticity of demand for VMT with respect to the price fuel of -0.22.

Estimates of the own-price elasticity of food demand are 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. We adopt a slightly more elastic value then the upper bound from that study, given that the own-price demand elasticity for tobacco is likely very small and is not represented in our treatment of the food sector here.

Our calibrated own price elasticity of demand for blended fuel is consistent with

[7]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.

[8]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.

empirical estimates. In particular, our estimate is slightly lower than the best estimate proposed by the US Department of Energy of 0.38 (DOE, 1996), and considerably smaller than the central value of 0.55 assumed by (Parry and Small, 2005). We choose a smaller value in order to be consistent with more recent estimates which report a smaller value (Small and Dender, 2007).

Our calibrated own-price elasticity of demand for miles with respect to the price of blended fuel is well within the central estimates provided by the literature and is consistent with the value implied by Parry and Small (2005). 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 -0.34.

Given calibration year crop production and export shares, and the total value of food, this implies the representative agent spends 0.035 of their income on food. Given calibration year data on fuel prices, fuel quantities, and miles-traveled, and assuming that the share of fixed costs of driving to total costs of driving was 0.60, this implies 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.[9] 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 the equilibrium price effects of RFS. [10]

Fuel Production

The ratio of the energy content of ethanol to gasoline, $\Gamma_F = 0.66$, is based on the low heating values of each fuel. Our linear specification for the production of blended fuel is not calibrated to an estimate of the elasticity of blended fuel. Rather, the elasticity of blended fuel will be determined only by the underlying elasticities of gasoline and ethanol.

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.[11]

[9] 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.

[10] Another source, which although more dated provides a finer definitional resolution for making comparisons, is the BEA's *Benchmark Input and Output Tables for 1992*. This dataset provides expenditure shares of 0.041 and 0.055, respectively, which are markedly closer to our estimates.

[11] 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.

Ethanol Production

The per unit ethanol input requirements in equation (A.10), 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 (2010).

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 of corn gluten feed and 0.02 kg of corn oil are jointly produced with each unit of ethanol. Consistent with the EPA (2010), 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.[12]

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 $0.032 per liter, which is the PADD average tariff plus rate plus fuel surcharge per liter 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

[12] 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).

plus fuel surcharge per liter 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.[13]

RFS Share Mandate

The RFS share mandate, θ_F, 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 identifies an estimate of θ_F.

Food Production

All crops that are not used for ethanol production or exported are used to produce food. The share of crop expenditures on food to the total value of food, 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 the benchmark value of labor used in food production, L_X.

The elasticities of substitution, σ_X, σ_Q and σ_V, in the food production function (Equation (A.14)) are provided in Table A.5. These parameters are selected to reflect the technical properties of food production. In particular, we choose σ_X to reflect near complementarity between crops and labor in the production of food. This prevents substitution from crops to labor that is unrealistic. We allow for much greater substitutability between hay, wheat and the corn-soybean index V, and the greatest substitutability between corn and soybeans. In 2003, the resulting own-price elasticities of crop demand for domestic food production range from -0.16 to -0.22 for the four crops used in food production which are broadly consistent with literature estimates for developed countries (see FAPRI *Searchable Elasticity Database*). In the text, we perform sensitivity analysis on the elasticities of substitution in the food production function to vary the implied crop demand elasticities for food production.

[13]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 (11)), we sum expenditures over four broad input categories: labor, capital, energy and fertilizer (Table A.4). Expenditures on labor and capital are from the USDA's ERS *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 ERS *Fertilizer Use and Price* data.[14] Second, expenditures on other variable inputs are from the CCR.[15] Fertilizer expenditures are disaggregated in the lower panel of Table A.4.

Land Supply Elasticities

The six δ_i in (A.7) are selected in order to match the supply response of the US land market to the elasticities taken from the literature and reported in Table A.3. Given the six δ_i, we select the six β_i in (A.7) in order to match the yields reported in Table A.1 in 2003, and adjusted each year afterwards to reflect exogenous growth in crop yields over time (see Section V below). Given the structure of the model, these β_i can be solved for as a function of δ_i such that the implied yields are almost identical to the targeted yields. To improve precision in matching estimated supply response to literature estimates, we re-calibrate the δ_i parameters each year to construct our baseline, and then again for each counterfactual run.

To select each δ_i vector, we perform an exhaustive search that seeks to minimize the error between the supply response implied between two model runs (taking the equilibrium resulting from the previous run as exogenous data) and the supply response implied by Table A.3 given the percent change in crop prices between the two model runs. Each search is highly non-linear and takes several days to complete. To improve computational time and precision, we exploit several optimization algorithms, including modern heuristic algorithms such as the Local Multistart Radial Basis Function (LMSRBF) algorithm developed by Regis and

[14]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.

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

Shoemaker (2007). We repeat this using multiple random re-starts and choose the vector that achieves the best supply response from the resulting candidates. The initial 2003 δ_i vector was selected to match supply response resulting from a 1% exogenous increase in ethanol. All baseline δ_i vectors are selected recursively using the preceding year's baseline equilibrium as exogenous data, starting from the 2003 baseline equilibrium. Each counterfactual δ_i vector for a given year is selected using the baseline equilibrium for that year as exogenous data. We isolate the δ_i vector for each baseline run using a baseline in which the VEETC is in place. We isolate the δ_i vector for each counterfactual run for our first regime which compares the RFS with the VEETC to the baseline in which the VEETC is in place. In total, these searches took about six months to complete.

To demonstrate the success of this approach, we point to the exhaustive validation exercise we perform in Section VII that attempts to demonstrate that the predicted land response of our model is in line with observed outcomes. We match observed land patterns well and our predictions for later years are in line with USDA Long-Term projections that pre-date the RFS.

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 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.[16]

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

$$R = D_{Gas}^{US} = S_{Crude}^{ROW} + S_{Crude}^{US} - D_{Crude}^{ROW} - D_{Dist}^{US} - D_{Other}^{US} \tag{A.15}$$

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.[17]

Differentiating this equation with respect to the price of crude oil and solving for

[16] 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.

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

the elasticity of excess supply facing US gasoline producers, η_R, we have:

$$\eta_R = \eta^{ROW}_{S,Crude}\left(\frac{S^{ROW}_{Crude}}{D^{US}_{Gas}}\right) + \eta^{US}_{S,Crude}\left(\frac{S^{US}_{Crude}}{D^{US}_{Gas}}\right)$$

$$- \eta^{ROW}_{D,Crude}\left(\frac{D^{ROW}_{Crude}}{D^{US}_{Gas}}\right) - \eta^{US}_{D,Dist}\left(\frac{D^{US}_{Dist}}{D^{US}_{Gas}}\right) - \eta^{US}_{D,Other}\left(\frac{D^{US}_{Other}}{D^{US}_{Gas}}\right). \tag{A.16}$$

To calibrate η_R using (A.16) 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 A.6. In 2003, total world crude considered in our framework is 4,545.8 billion liters (28,954 million barrels). [18] 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 A.6 reports the central literature values for the elasticities on the right-hand side of (A.16) 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 annual response to a change in the yearly average price of crude oil. In this time frame, we can expect both supply and demand adjustments, such as 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

[18]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 A.6 will be slightly below the values reported by the EIA.

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 (A.13) 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

Two considerations are important for comparing our crude oil elasticities to other biofuel studies. First, our model measures the annual impact of the RFS on greenhouse gas emissions and we therefore use short run elasticities for crude oil supply and demand. Our elasticities should, and do, differ from those used by studies that analyze the aggregate impact of the RFS over many years and therefore use medium to long run elasticities (Rajagopal et al., 2011; Thompson et al., 2011). Second, the elasticities we specify are for the supply and demand of crude oil and should not be directly compared to the elasticities of gasoline supply and demand used elsewhere (Chen and Khanna, 2012; Drabik and de Gorter, 2011).

Rest-of-world Crop Demand

The crop export demand elasticities, η_i in equations (A.12), 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:

$$\gamma_{ROW,i} = \frac{-\eta_{S,i}^{ROW} S_i}{\eta_{D,i}^{ROW} D_i - \eta_{S,i}^{ROW} S_i} \tag{A.17}$$

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 taken 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.

In our central case, the percentages 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 (2010).[19] 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.

IV. Emissions Calculations

The emissions factors corresponding to the ϕs in equations (18) are (19) are presented in Table A.7 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).[20] 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 (2010).

Overview

The 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, as well

[19]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 (2010) 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.

[20]We use global warming potentials from IPCC Third Assessment Report to calculate CO_2e.

as on-farm emissions.[21] 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, $\phi_{N,k}$, 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 two countries, 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 (2010), Searchinger et al. (2008) and Fargione et al. (2008)).

Gasoline

The lifecycle emissions of gasoline, ϕ_G, are 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).

Ethanol Production and Combustion

The lifecycle emissions from ethanol production are assumed to be 0.6 kgCO_2e/liter. This factor assumes a representative natural gas fired dry-mill ethanol plant, consistent with the US (EPA, 2010). We also account for the release of CH_4 and N_2O from ethanol combustion, which totals 0.02 kgCO_2e/liter (EPA, 2010).[22] Combining, ϕ_E is 0.62 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, 2010). 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.

International 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

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

[22]While the CO_2 released during ethanol combustion is completely offset by carbon uptake during the growing of corn, this is not the case for other greenhouse gases.

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.[23] 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. For completeness, we also report a plausible upper bound of the impact on emissions related to changes in rest of world crude oil consumption by attaching positive emissions coefficients on other crude products. Even with this plausible upper bound, the main conclusions of our analysis are not affected.

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 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:

$$D_{Elect} = S_{Resid} + S_{Other} \tag{A.18}$$

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 (A.18), 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

[23]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.

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.[24]

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 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.[25]

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.

In our central case, where we account for emissions only for 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

[24] 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).

[25] 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.

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).

As part of our analysis of the emissions from the world crude market below, we also consider potential emissions from other crude products in the US and the rest of the world. This category is an aggregate of crude oil used for all products other than gasoline and distillates, including residual fuels, jet fuel, kerosene, LPG and other petroleum products as defined by the EIA. To these categories we assign emissions factors of 1.7 kgCO_2e/liter (266.5 kgCO_2e/barrel) and 2.1 kgCO_2e/liter (334.5 kgCO_2e/barrel) for the US and rest of world respectively.

We back out these emissions factors from the EIA International Energy Statistics reported total CO_2 emissions from petroleum production in 2003. First, for both the US and ROW we deduct from total 2003 CO_2 emissions, the CO_2 emissions from gasoline and distillate consumption calculated using the emissions factors described above and the 2003 quantities of gasoline and distillate consumption reported by the EIA. We then divide these quantities of CO_2 by the quantity of petroleum that we categorized as other crude products. This provides emissions per unit other petroleum products in both the US and ROW.

The difficulty in calculating emissions factors for our category of other crude products lies in assigning a level of emissions to the EIA defined other petroleum products, since this petroleum may not be combusted, but rather used as a manufacturing input or lubricant. Our method of deriving an emissions factor for our category of other crude products implicitly uses EIA assumptions regarding the composition of crude products in this category and their resulting emissions. That the emissions factors for are other crude category are lower than the emissions factors for gasoline or distillates is reasonable, given that the EIA defined category of crude is not necessarily combusted. In addition, our category of other crude oil products is made up of a large share of LPG (29.4% in US, 18.1% in ROW) which has an emissions factor that is 40% lower than that of gasoline or distillates (1.5 kgCO_2e/liter).

Analysis of Different Crude Oil Market Assumptions

While excluding the change in emissions arising from adjustments in other non-gasoline and non-distillate petroleum products affects the magnitude of leakage from the world crude oil market, it does not, in general, affect whether we predict the RFS to have a positive or negative impact on emissions. Table A.11 reports the net impact on emissions of the RFS for the years 2012 and 2015 under our central treatment of emissions from the rest of world crude market, as well as two alternative treatments. First, we account for emissions only for crude used to produce gasoline, both domestically and in the rest of the world. Since the gasoline used outside the US accounts for only about 16% of rest-of-world crude oil use, leakage from the world crude oil market is substantially lower than in our central case. Second, we report an estimate for the change in emissions owing to a change in demand for all crude products. This approach provides a plausible upper bound on emissions from adjustments in the world crude oil market, provided there are not significant demand-side adjustments.[26] When accounting for adjustments in all crude products, leakage from the world crude oil market roughly doubles relative to the central case, because other crude products are a considerable portion of the world crude market. With all of the approaches we consider for calculating emissions from the crude oil market, the RFS will increase emissions in 2012 and 2015 when the VEETC is renewed. Swapping the RFS for the VEETC will reduce emissions when only changes in crude of gasoline, or only crude for gasoline and distillates are considered in the emissions calculations, but have will a very small positive impact on emissions when all crude products are included in the emissions calculations.

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. In our central case, 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.[27] Crop specific synthetic fertilizer application rates are from our agricultural dataset. Nitrogen additions from 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.[28] To account for these uncertainties, as sensitivity analysis we adjust the agricultural emissions factors to reflect alternative

[26] The change in other crude products is net of both demand and supply-side adjustments. By capturing emissions from the change in the demand for other crude products we are assuming the change in emissions from supply-side adjustments are of the dirtier crude product, hence this is a plausible upper bound with respect to supply-side adjustments. Since the change in other crude products also includes the change in other crude products from the demand side as well, with respect to the demand side we are only accounting for the increase in emissions from the other crude product and not the non-crude alternative. To the extent that demand-side adjustments also lead to significant increases in the non-crude alternative, we are still not counting these emissions, and hence this may not be an upper bound in this case. In order for this to be significant, however, we would require both a large demand-side increase in the end-use product as well as a large share of the non-crude alternative relative to the other crude product with small substitutability between the two inputs. With respect to the end-use sectors that consume other crude products, we think this is highly unlikely, and so on net, this should be thought of as a plausible upper bound.

[27] 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).

[28] 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.

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 (2010). Relative to the central case, emissions from soybean production are three times greater in low agricultural N_2O case.[29] 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 are estimated using IPCC default methods which assume that all carbon in lime applied to agricultural soils is converted CO_2 (IPCC, 2006).

We use GREET 1.8c (Wang, 2009) to estimate the lifecycle emissions of producing nitrogenous (N), phosphate (P), and potassium (K) fertilizers, pesticide and agricultural lime. The farm input production lifecycle includes 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, 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.[30]

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 (2010), 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

[29] 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).

[30] 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.

carbon stored in below-ground biomass and soils of CRP land is released within the next 30 years. Consistent with standard practice (see EPA (2010)), we amortize total emissions from land use conversion over 30 years, with no discounting.[31] 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 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_2e/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_2e/ha (EPA, 2010). 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, 2010).[32] 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

[31] 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.

[32] The EPA assessment of the RFS (EPA, 2010) 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.

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 (2010).

V. 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.

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.[33]

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 AEO 2010, increasing monotonically from $0.40 per liter ($63.37 per barrel) in 2009 to $0.47 per liter ($73.85 per barrel) in 2015 (in constant 2003$). 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 positive nature of crude prices in the AEO 2010, we linearly project crude oil prices between 2010 and 2012. For the years 2013 to 2015 we simply use the values taken directly from the AEO 2010 (adjusted to constant 2003$). Note, in generating our counterfactual baseline this is the price path that we impose exogenously. However, when we simulate the impact of the RFS, the price of crude oil is allowed to endogenously adjust from this initial level, according to (A.13).

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 2010 Agricultural Projections.

We allow ethanol production technology to improve following US EPA projections (EPA, 2010). 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, 2010). The corn-to-ethanol conversion ratio also improves. In 2015, the average ethanol conversion efficiency is 0.42

[33]Calculated using data from the USDA's Foreign Agricultural Service (FSA) *Production, Supply and Distribution Online* (PSD) dataset.

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 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.

VI. Other US Biofuel Policies

RFS for Advanced Biofuels

The RFS for advanced biofuels expands from 2.3 billion liters in 2009 to 20.8 billion liters in 2015, and reaches a maximum of 79.5 billion liters by 2022. This mandate applies to any biofuel that achieves 50% lifecycle emissions savings or greater. Advanced biofuels span three dominant technologies: cellulosic ethanol, biomass based diesel, and sugarcane ethanol imported from Brazil and Caribbean Basin Initiative (CBI) countries. In the short-run (up to 2015), each technology faces challenges for expansion. This is in sharp contrast to corn ethanol and the corresponding RFS for conventional biofuels, which the EPA has determined can be met domestically given past production and plants currently being constructed/expanded (EPA, 2010). Of these three advanced technologies, biomass-based diesel currently has the largest share of US consumption by far, although it is a diesel substitute and in relative and absolute terms corresponds to a tiny share of the market for US transportation fuels.

The other two advanced biofuel technologies, cellulosic and imported sugarcane ethanol, are substitutes for gasoline, but so far have had even lower levels of penetration in the market for US transportation fuels. Cellulosic ethanol has its own aggressive sub-mandate within the RFS for Advanced biofuels, although EISA 2007 includes a "cellulosic loophole" which effectively allows the EPA to scale down the RFS for cellulosic biofuels if production is not there (see below). Since cellulosic ethanol continues to not be cost-effective relative to corn ethanol, producers have no incentive to expand production in the presence of this loophole. In the final rules for 2010, 2011, and 2012, the EPA has in fact exercised this legal authority, lowering the effective RFS for cellulosic biofuels *to* 7%, 3%, and 2%, respectively, of the statutory level stated in EISA 2007. Likewise, imports of ethanol to the US have averaged roughly 1 billion liters per year between 2006-2011, and are likely to remain at low volumes in the short-run.[34]

[34]Data on ethanol imports is taken from the Renewable Fuels Association and does not distinguish between ethanol produced from corn and sugarcane. In all likelihood, almost all of this is sugarcane ethanol

Given these trends, we think there are legitimate reasons to question whether the volumes for advanced biofuels specified under EISA 2007 will actually be achieved in the short run and at volumes large enough to be of major economic consequence.[35] Given this, as well as the lack of credible data on feedstock production and technological conversion efficiency for advanced biofuels, we do not consider the RFS for advanced biofuels in our analysis.

The Cellulosic Loophole in EISA 2007

According to the federal law (specifically CAA section 211(o)(7)(D)(i)), as adjusted by EISA 2007, the "EPA is required to make a determination each year regarding whether the required volumes of cellulosic biofuel for the following year can be produced. For any calendar year for which the projected volume of cellulosic biofuel production is less than the minimum required volume, the projected volume becomes the basis for the cellulosic biofuel standard [our emphasis]. In such a case, the statute also indicates that EPA may also lower the required volumes for advanced biofuel and total renewable fuel (40 FR 14669 (2010-03-26))."

In effect, this "Cellulosic Loophole" allows the EPA administrator to revise the cellulosic mandates specified in EISA 2007 to the amount of cellulosic ethanol that is anticipated to be in production in the following year when specifying the annual Final Rules regarding the RFS. This loophole has been exercised repeatedly for all of the year's in which EISA 2007 has mandated significant quantities of cellulosic ethanol. In the 2010 Final Rule of the RFS, the EPA revised down the statutory requirement of 100 million gallons to a cellulosic mandate of 5.04 million gallons, or 93% lower than the amount specified under EISA 2007 (pg. 14718, 40 FR 14669 (2010-03-26)). The 2011 Final Rule, revised down the statutory requirement of 250 million gallons to a cellulosic mandate of 6.6 million gallons, or 97% lower than the statutory requirement (Table I.D.1, 40 FR 76790 (2010-12-09)). In the 2012 Final Rule, the EPA revised down the statutory requirement of 500 million gallons to a cellulosic mandate of 8.65 million gallons, or 98% lower than the statutory requirement (Table I.A.3-1, 40 FR 1320 (2012-01-09)).

Import Tariff

Historically, the other major federal biofuel policy in the US, along with the RFS and VEETC, was an import tariff of $0.15/liter, which offset the VEETC for imported ethanol. The tariff was allowed to expire at the end of 2011, along

from Brazil and Caribbean Basin Initiative (CBI) countries. Sugarcane ethanol imports from Brazil and CBI countries face several challenges for expansion in the short-run which are discussed in detail in EPA (2010). Broadly these issues include: the presence of non-tariff trade barriers which continue to restrict the competitiveness of imports, limits to the rate at which production can be scaled up in Brazil and CBI, and the fact that ethanol imported from Brazil and CBI countries must first be converted from hydrous to anhydrous ethanol in order to be compatible with the US market and the rate at which dehydrating capacity can be scaled up is also limited. These issues affect long-term prospects as well, with the EPA analysis predicting a small role for ethanol imports from Brazil and CBI countries by 2022, accounting for only 8.4 billion liters of the 79.4 billion liter advanced RFS by 2022 (EPA, 2010).

[35] We are also suspicious regarding long-run (through 2022) prospects as well. After 2015, the RFS for cellulosic biofuels forms the bulk of the requirement for the RFS for advanced biofuels. Given limits in the EPA's ability to revise the bio-mass based diesel standard going forward, and the criticisms that would escalate if the EPA mandates large consumption of sugarcane ethanol from foreign sources, in all likelihood the EPA will have to revise the RFS for advanced biofuels in the future to reflect the adjustments it will need to make regarding the RFS for cellulosic biofuels.

with the VEETC. The expiration of the tariff should effectively have no impact on the demand for imported ethanol because the the VEETC expired concurrently. We abstract from ethanol imports in our framework, even after the expiration of the tariff, because US ethanol imports have historically been low and because of the short-run limitations to the expansion in sugarcane-based ethanol imports, as discussed above.

State-Level Policies

While the RFS and VEETC influence the total amount of ethanol used in the US, several states encourage biofuel adoption through state-level biofuel mandates. Likewise, in California biofuels can be used to comply with the Low Carbon Fuel Standard. An assortment of ethanol production subsidies, loan guarantees, and tax credits are also prevalent at the state level.[36]

VII. Model Validation

Comparison of Model Predictions to Historic Data

We calibrate the model to 2003 so we are able to compare our model's predictions against several years of observed data for which the RFS was largely considered to be non-binding. Table A.8 presents our out-of-sample model predictions averaged over the years 2004-2009 against observed data over that period.[37] Data for individual model years generally are similar to those reported here, with the caveat that, since we do not explicitly model commodity stocks in our model, our model predictions are smoother than those observed. Observed data is more variable, since various exogenous factors impact the amount of commodities stored or drawn down in a given year, such as droughts in individual commodity markets (for instance, wheat in 2007-2008), or interactions with other exogenous price swings elsewhere in the macroeconomy.

For corn, our model predictions are on average off by -1.78%, which suggests a good level of fit. Likewise, soybeans, wheat, and CRP predictions are off by similar margins. Hay exhibits slightly more error, at 5.88%, which likely reflects the fact that hay is the slack land-use in our model, but also because small deviations in observed hay yields magnify deviations relative to our model predictions. Cotton is off even more, with average deviations of -14.75%, although this is amplified by the fact that the base for cotton is orders of magnitude smaller than that for other crops. Our corn ethanol predictions are slightly higher, 8.62% greater, than that observed over this period, although in magnitude terms, we are off by slightly less than half a billion gallons for a given year.

Figure 2 plots a two-year moving average of our measure of CRP land (General signup plus Continuous, Non-CREP signup) against the commodity price index for price received (pegged to 1990 -1992). Starting in 2007 and continuing through 2008, commodity prices started undergoing a considerable structural change. The commodity price index for prices received grew from a moving-average value of roughly 115 in 2006 to roughly 143 in 2008, denotes growth in average prices received

[36]For a complete list of state level biofuel policies see the US Department of Energy's Alternative Fuels & Advanced Vehicles Data Center (http://www.afdc.energy.gov/afdc/laws/state).

[37]Data for individual model years are available from the authors by request.

of roughly 24%. By 2010 this sloughs off slightly to an index value of 136, which still denotes an increase in the average commodity price level relative to 2006 of roughly 19%. Not surprisingly, our measure of CRP starts to decline in 2008, resulting in a shedding of 2.33 million hectares between 2008 and 2010, given the data reported in Table A.10. Relative to the 2003 total, this is a reduction of 17.2%—a non-negligible reduction in CRP acres over this period.

For sake of comparison, our model finds a 0.2 million hectares or roughly half a million acre fall in CRP due to the RFS in 2012 when the VEETC is continued (see Table A.10). This is internally consistent with the CRP acreage elasticity of -0.07 (as reported in Table 1, given the change in the returns to cropland arising due to the change in the RFS. In this year our model predicts the RFS will bind by 6.1 billion liters (see Table 2), requiring an additional 1.1 million hectares of corn land devoted to ethanol production (see Table A.10). This implies a fall in CRP acres of 0.03 hectares for every 1,000 liters of ethanol added by the RFS, relative to an increase in corn hectares devoted to ethanol production of 0.18 hectares per 1,000 liters. We believe our model's prediction for this fall in CRP is conservative and reasonable. Further, it is fully consistent with observed changes in CRP acreages reported in recent years. Between 2008 and 2009 corn ethanol expanded by 2.4 billion liters and corn acreage expanded by 0.28 million hectares, whereas CRP acreage fell by 0.38 million hectares.

Comparison of Model Predictions to 2006-2009 Average of USDA Long-Term Projections

Table A.9 compares our model predictions against an average of the USDA's Long-Term Projections for the years 2006, 2007, 2008, and 2009. We compare vis-a-vis an average of Long-Term Projections, given the large degree of variation in the projections over this time period, owing to the considerable changes in commodity markets observed in these years and changes in the assumptions underlying the USDA estimates, in particular prior to the EISA 2007 being fully embedded into their projections.[38] In general, our estimates are largely consistent with the USDA Long-Term Projections.

VIII. Additional Sensitivity Analysis

In light of research suggesting that the efficiency and lifecycle emissions of ethanol production is rapidly improving (Liska et al., 2009), we conducted sensitivity analysis on the energy and corn requirements of ethanol production (Table A.18). Lowering the energy requirements of ethanol production reduces the net change in emissions due to the RFS by increasing intended emissions savings per liter of ethanol added, but has a negligible impact on land and fuel market leakage. Reducing the corn requirements of ethanol production increases intended emissions savings and increases the quantity of ethanol in the baseline, and therefore reduces the quantity of ethanol added by the RFS. In our results, the large differences in the baseline level of ethanol and the resulting land market adjustments mask two additional impacts of lowering the corn required for ethanol production. First, the

[38] Hay and CRP are not reported here since the USDA Long-Term Projections do not include projections for hay or land held in the CRP.

RFS will have smaller impacts on land markets, therefore lowering land market leakage. Second the price of ethanol, and therefore the price of blended fuel will be less responsive to increases in the price of corn and domestic fuel market leakage will be larger.

IX. Additional Results

Table A.12 presents the impact of the RFS on the prices of crops. Table A.13 presents the total change in emissions, intended emissions savings and each primary source of leakage per unit of ethanol added by the RFS. Tables A.16 and A.17 replicates the sensitivity analysis presented in the text for the year 2012. Table A.18 reports emissions results under varying assumptions regarding the efficiency of ethanol production for the year 2015.

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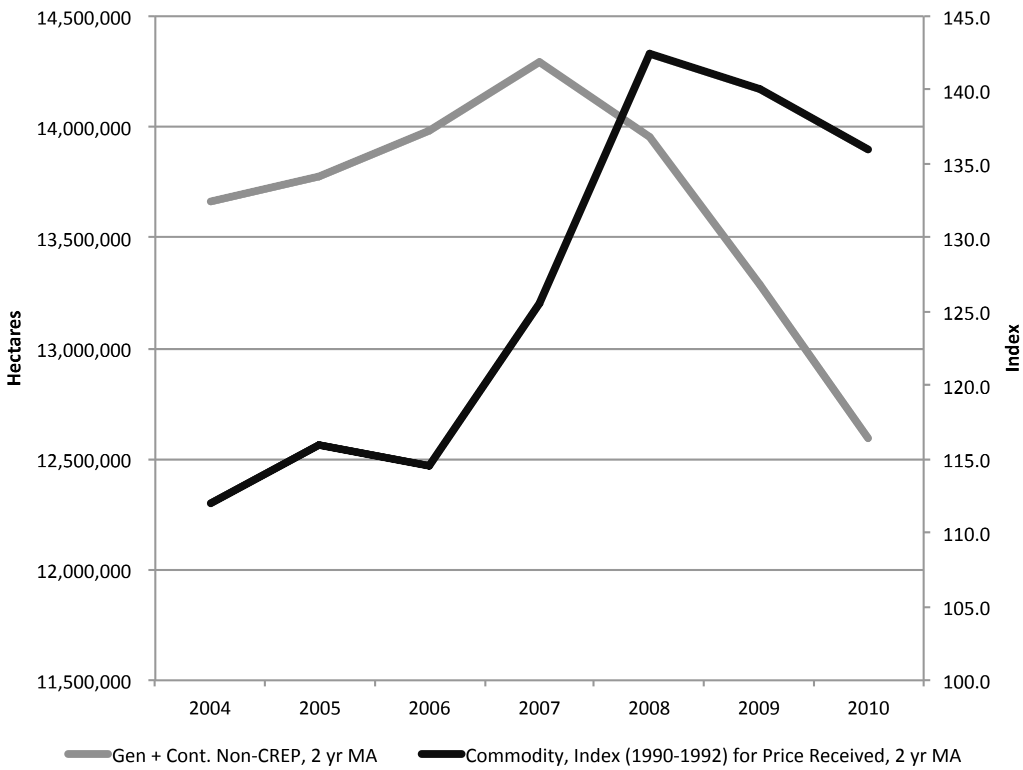

Figure 2. : CRP Acres Against Commodity Price Index (Price Received)

Table A.1—: 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	$1,036.32	NASS
Fuel Quantities		
VMT (trillion passenger miles)	2.69	FHWA
Blended Fuel (billion liters)	499.97	
Ethanol (billion liters)	10.39	FHWA
Regular Gasoline (billion liters)	490.28	FHWA
Domestic Crude Oil (billion barrels)	3.12	GCH, CSD, BNI
Fuel Prices		
VMT ($/passenger mile)	$0.19	
Blended Fuel ($/liter)	$0.41	
Ethanol ($/liter)	$0.35	
Regular Gasoline ($/liter)	$0.23	AER
Crude Oil ($/liter)	$0.18	AER
Labor Tax Rate (%)	36.59%	
Fuel Tax ($/liter)	$0.10	FHWA
CRP Rental Payment ($/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.

Table A.2—: Key Parameter Values

Parameter	Value	Source
Households		
Elasticity of substitution, Consumer, σ_U	0.5	See page A.7
Elasticity of substitution, Consumer, σ_W	0.09	See page A.7
Elasticity of substitution, VMT, σ_M	0.21	See page A.7
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, λ_{E,Y_1}	2.56	Wang (2009)
Labor expenditures per liter ethanol	$0.13	Farrell et al. (2006)
Regular Gasoline and Crude Oil		
Elasticity of substitution, Regular Gasoline Production, σ_P	0.06	See Text
Share of per unit crude oil cost to total cost of gasoline	0.61	GCH, CSD, BNI
Own price elasticity of crude oil supply	0.50	See Text
Crude oil yield for regular gasoline	0.47	GCH, CSD, BNI

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

Table A.3—: Targeted Crop Area Elasticities

	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 A.4—: 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 A.5—: Additional Calibration Parameters

Model Parameter	Value	Source
Households		
Expenditure Share on Food	0.035	
Expenditure Share on VMT	0.065	
Crop Export Markets		
Elasticity of ROW demand for US corn exports	-0.65	
Share of corn exports to Total US Production	0.19	PSD
Elasticity of ROW demand for US soybean exports	-0.6	
Share of soybean exports to Total US Production	0.36	PSD
Elasticity of ROW demand for US wheat exports	-0.55	
Share of wheat exports to Total US Production	0.49	PSD
Elasticity of ROW demand for US cotton exports	-0.75	
Share of cotton exports to Total US Production	1	PSD
Ethanol		
Average tariff rate (plus fuel surcharge) per liter of ethanol	$0.02	
Gasoline and Crude Oil		
Share of crude oil cost to total cost of gasoline per liter	0.61	EIA
Crude oil yield for gasoline	0.47	EIA
Food Production		
Elasticity of substitution, Food Production, σ_X	0.08	
Elasticity of substitution, Food Production, σ_Q	0.25	
Elasticity of substitution, Food Production, σ_V	0.30	
Share of crop expenditures on food to total food expenditures	0.19	

Table A.6—: 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 (A.16). 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 A.7—: Final Product/Activity Emissions Factors

	Central	Low	High	Source
Gasoline (kgCO_2e/liter)	3.0			
Combustion	2.4	-	-	EPA (2010)
Production	0.6	-	-	EPA (2010)
Ethanol (kgCO_2e/liter)				
Combustion	0.02	-	-	EPA (2010)
Production	0.6	-	-	EPA (2010)
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 (2010)

Notes: See Appendix for description of calculations. N_2O emissions from agricultural production depend on crop yields and therefore vary 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.

Table A.8—: Comparison of Out of Sample Model Predictions to Historic Data

	2003	2004-2009, Avg.
Land Harvested (million hectares)		
Corn, Our Prediction	31.38	33.14
Corn, USDA	31.38	33.74
% Difference	0.00%	-1.78%
Soybeans, Our Prediction	29.33	29.18
Soybeans, USDA	29.33	29.34
% Difference	0.00%	-0.56%
Hay, Our Prediction	25.65	26.07
Hay, USDA	25.64	24.63
% Difference	0.02%	5.88%
Wheat, Our Prediction	21.47	20.69
Wheat, USDA	21.47	20.46
% Difference	0.00%	1.08 %
Cotton, Our Prediction	4.86	3.76
Cotton, USDA	4.86	4.41
% Difference	-0.01%	-14.75%
CRP, Our Prediction	13.57	13.41
CRP, USDA	13.57	13.61
% Difference	0.00%	-1.50%
Ethanol Quantities (billion liters)		
Ethanol Baseline Quantities	10.4	27.6
Total US Demand, RFA	10.4	25.4
% Difference	0.00%	8.62%

Notes: USDA value for corn includes total harvested for silage and for grain.

Table A.9—: Comparison of Out of Sample Model Predictions to Average of 2006-2009 USDA Long-Term Projections

	2010	2012	2015
Harvested Land (million hectares)			
Corn Acres, Our Baseline Estimate	33.86	33.90	33.38
Corn Acres, Our Post-RFS Estimate	34.27	34.98	35.33
Corn Acres, Avg. 2006-2009 LT Proj.*	32.67	33.18	33.07
% Difference, Baseline	3.65%	2.18%	0.93%
% Difference, Post-RFS	4.91%	5.45%	6.83%
Soybean Acres, Our Baseline Estimate	29.08	29.38	29.44
Soybean Acres, Our Post-RFS Estimate	28.97	29.05	28.87
Soybean Acres, Avg. 2006-2009 LT Proj.	28.37	28.00	27.75
% Difference, Baseline	2.51%	4.94%	6.10%
% Difference, Post-RFS	2.13%	3.77%	4.04%
Wheat Acres, Our Baseline Estimate	20.70	20.57	22.44
Wheat Acres, Our Post-RFS Estimate	20.62	20.30	22.08
Wheat Acres, Avg. 2006-2009 LT Proj.	20.35	20.17	20.03
% Difference, Baseline	1.74%	1.97%	12.02%
% Difference, Post-RFS	1.34%	0.61%	10.23%
Cotton Acres, Our Baseline Estimate	3.75	3.72	3.77
Cotton Acres, Our Post-RFS Estimate	3.69	3.57	3.48
Cotton Acres, Avg. 2006-2009 LT Proj.	4.40	4.51	4.56
% Difference, Baseline	-14.86%	-17.61%	-17.37%
% Difference, Post-RFS	-16.23%	-21.00%	-23.83%
Ethanol (billion liters)			
Ethanol, Our Baseline Estimate	41.79	43.94	45.44
Ethanol, Avg. 2006-2009 LT Proj.**	38.31	40.47	43.23
% Difference	8.29%	7.92%	-4.94%

Notes: *: Does not include corn land harvested for silage, since silage is not tracked by USDA L-T Projections. **: Figure for 2012 and 2015 takes corn for ethanol and converts to ethanol using conversion parameters from our model for the given year. Figure for 2009 comes from the RFA and represents total US demand for ethanol. ***: Estimate computed is based on a per gallon of blended fuel share mandate on ethanol consumption, which is calculated annually by taking the RFV statutory quantities and dividing by the expected blended fuel consumption (post-policy) for a given year.

Table A.10—: Change in CRP For Years 2003-2010 (Million hectares)

Year	General	Cont. Non-CREP	Total	Annual Change	% Annual Change
2003	12.80	0.77	13.57		
2004	12.88	0.88	13.76	0.19	1.43%
2005	12.84	0.96	13.80	0.04	0.28%
2006	13.13	1.04	14.17	0.37	2.70%
2007	13.32	1.10	14.42	0.25	1.78%
2008	12.36	1.12	13.48	-0.94	-6.52%
2009	11.90	1.20	13.10	-0.38	-2.84%
2010	10.79	1.30	12.09	-1.01	-7.73%

Notes: Data taken from *Conservation Reserve Program Annual Summary and Enrollment Statistics* for years 2003 through 2010.

Table A.11—: Alternative Calculations of Leakage from World Crude Oil Market, 2015

	2012	2015
RFS (VEETC Renewed)		
ROW Crude Baseline (billion liters)	4513.0	4667.4
ROW Crude Change (billion liters)	1.5	2.9
Change in US Distillates	0.1	0.1
Change in US Other	0.1	0.3
Change in ROW Gasoline	0.3	0.5
Change in ROW Distillates	0.4	0.7
Change in ROW Other	0.6	1.3
Leakage from world crude market ($TgCO_2e$)		
Gasoline Only	0.6	1.2
Gasoline and Distillates	1.8	3.6
All Crude Products	3.4	6.7
Net Change in Emissions (TgCO2e)		
Gasoline Only	0.4	2.1
Gasoline and Distillates	1.6	4.5
All Crude Products	3.2	7.6
RFS (VEETC Swapped)		
ROW Crude Baseline (billion liters)	4513.0	4667.4
ROW Crude Change (billion liters)	2.4	3.9
Change in US Distillates	0.1	0.2
Change in US Other	0.2	0.3
Change in ROW Gasoline	0.4	0.7
Change in ROW Distillates	0.6	1.0
Change in ROW Other	1.0	1.7
Leakage from world crude market ($TgCO_2e$)		
Gasoline Only	1.0	1.6
Gasoline and Distillates	2.9	4.8
All Crude Products	5.5	9.0
Net Change in Emissions ($TgCO_2e$)		
Gasoline Only	-6.5	-5.2
Gasoline and Distillates	-4.6	-2.0
All Crude Products	-2.0	2.2

Notes: Our category of other crude products includes residual fuels, jet fuel, kerosene, LPG and EIA defined other petroleum products.

Table A.12—: Impact of RFS on Crop Prices

	2012	2015
RFS (VEETC Renewed)		
Baseline Corn Price($/metric ton)	126.2	136.7
Change in Corn Price	12.6%	25.3%
Baseline Soybean Price ($/metric ton)	300.1	331.8
Change in Soybean Price	0.7%	3.0%
Baseline Hay Price ($/metric ton)	127.6	194.4
Change in Hay Price	5.9%	10.3%
Baseline Wheat Price ($/metric ton)	160.2	133.8
Change in Wheat Price	5.6%	20.0%
RFS (VEETC Swapped)		
Baseline Corn Price($/metric ton)	126.2	136.7
Change in Corn Price	12.1%	24.6%
Baseline Soybean Price ($/metric ton)	300.1	331.8
Change in Soybean Price	0.7%	2.9%
Baseline Hay Price ($/metric ton)	127.6	194.4
Change in Hay Price	5.9%	10.2%
Baseline Wheat Price ($/metric ton)	160.2	133.8
Change in Wheat Price	5.5%	19.8%

Table A.13—: Leakage per Unit Added Ethanol

	2010	2012	2015
RFS (VEETC Renewed)			
Net Change in Emissions (kgCO_2e/liter)	0.10	0.27	0.40
Intended Emissions Savings, I	0.82	0.83	0.85
Net Leakage	0.91	1.09	1.25
Land Market Leakage	0.34	0.58	0.72
From the Domestic Land Market, L^{DA}	-0.25	-0.08	-0.07
From the World Land Market, L^{WA}	0.59	0.66	0.79
Fuel Market Leakage	0.57	0.51	0.53
From the Domestic Fuel Market, L^{DF}	0.30	0.22	0.22
From the World Crude Oil Market, L^{WF}	0.27	0.29	0.31
RFS (VEETC Swapped)			
Net Change in Emissions (kgCO_2e/liter)	-1.57	-0.79	-0.18
Intended Emissions Savings, I	0.82	0.83	0.85
Net Leakage	-0.75	-0.04	0.67
Land Market Leakage	0.34	0.59	0.73
From the Domestic Land Market, L^{DA}	-0.26	-0.08	-0.07
From the World Land Market, L^{WA}	0.60	0.67	0.80
Fuel Market Leakage	-1.09	-0.55	-0.06
From the Domestic Fuel Market, L^{DF}	-1.68	-1.05	-0.49
From the World Crude Oil Market, L^{WF}	0.59	0.50	0.43

Table A.14—: Impact of RFS on Land and Fuel Markets Relative to No-VEETC Baseline

	2010	2012	2015
Ethanol Baseline, No VEETC (billion liters)	22.7	24.5	31.2
Change in Ethanol due to RFS	23.0	25.8	25.8
Domestic Corn Baseline (million ha)	30.5	31.0	31.7
Additional Corn Required	4.1	4.4	4.3
Change in Domestic Corn	3.8	4.4	3.6
From Other Crops	-2.6	-3.3	-2.9
From Land held in CRP	-1.0	-1.2	-0.8
Change in World Non-Agricultural Land	-1.7	-2.0	-2.3
Baseline Blended Fuel Price ($/liter)	0.6	0.6	0.7
Change in Price of Blended Fuel	-1.9%	-1.7%	-1.3%
Baseline Ethanol Price ($/liter)	0.3	0.3	0.3
Change in Price of Ethanol	20.9%	32.1%	39.9%
Baseline Gasoline Price ($/liter)	0.4	0.4	0.5
Change in Price of Gasoline	-4.5%	-5.2%	-5.5%
Baseline Blended Fuel (billion liters)	462.8	470.0	468.7
Change in Blended Fuel	3.3	3.1	2.7
Baseline Crude Oil Price ($/liter)	0.4	0.5	0.5
Change in Crude Oil Price	-5.8%	-6.6%	-6.9%
Baseline World Crude Oil (billion liters)	2083.0	2163.8	2217.9
Change in World Crude Oil	2.4	2.8	3.1

Table A.15—: Leakage per Unit Added Ethanol Relative to No-VEETC Baseline

	2010	2012	2015
Net Change in Emissions (kgCO2e/liter), $dGHG$	0.30	0.27	0.26
Intended Savings, I	0.84	0.86	0.87
Total Leakage	1.14	1.13	1.13
Total Land Market Leakage	0.54	0.54	0.55
Leakage in Domestic Land Market	-0.05	-0.07	-0.16
Leakage from World Land Market	0.60	0.61	0.71
Total Fuel Market Leakage	0.59	0.59	0.58
from domestic fuel market	0.32	0.30	0.27
from world crude market	0.27	0.29	0.31

Table A.16—: Emissions in 2012 Under Alternative Parameter Assumptions, Fuel Markets

Crude Oil Excess Supply Elasticity Fuel and VMT Elasticity of Demand	Central Central	Low Central	High Central	Central Low	Central High
RFS (VEETC Renewed)					
Baseline Ethanol Consumption (billion liters)	43.9	45.4	43.2	44.9	42.9
Change in Ethanol Consumption	6.1	4.6	6.8	5.0	7.1
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.27	0.58	0.12	0.19	0.34
Intended Savings, I	0.83	0.83	0.83	0.83	0.83
Domestic Land Market Leakage, L^{DA}	-0.08	-0.10	-0.07	-0.08	-0.07
World Land Market Leakage , L^{WA}	0.66	0.68	0.65	0.68	0.65
Domestic Fuel Market Leakage, L^{DF}	0.22	0.59	0.05	0.12	0.30
World Fuel Market Leakage, L^{WF}	0.29	0.24	0.32	0.30	0.29
RFS (VEETC Swapped)					
Baseline Ethanol Consumption (billion liters)	43.9	45.4	43.2	44.9	42.9
Change in Ethanol Consumption	5.8	4.4	6.5	4.9	6.8
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.79	-0.51	-0.92	-0.73	-0.82
Intended Savings, I	0.83	0.83	0.83	0.83	0.83
Domestic Land Market Leakage, L^{DA}	-0.08	-0.09	-0.07	-0.08	-0.07
World Land Market Leakage , L^{WA}	0.67	0.69	0.66	0.68	0.66
Domestic Fuel Market Leakage, L^{DF}	-1.05	-0.73	-1.21	-0.98	-1.10
World Fuel Market Leakage, L^{WF}	0.50	0.45	0.53	0.48	0.52

Notes: Elasticity of crude oil excess supply is 0.25, 0.5 and 0.75 in the low, central and high cases respectively. The elasticity of world crude oil demand is -0.01, -0.02 and -0.03 in the low, central and high cases respectively. Fuel and VMT elasticities of demand are varied by jointly modifying the elasticities of substitution, σ_U, σ_W, and σ_M in equations (A.5). The high case increases the elasticities of blended fuel and VMT demand by 0.1 from their central values whereas the low case considers a joint decrease in both elasticities by 0.1.

Table A.17—: Emissions in 2012 Under Alternative Parameter Assumptions, Land Markets

Elasticities of Crop Demand for Food Production Agriculture and Land Use Emissions	Central Central	Low Central	High Central	Central Low	Central High
RFS (VEETC Renewed)					
Baseline Ethanol Consumption (billion liters)	43.9	41.9	47.3	43.9	43.9
Change in Ethanol Consumption	6.1	8.1	2.6	6.1	6.1
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.27	0.36	0.12	-0.18	1.11
Intended Savings, I	0.83	0.83	0.83	0.88	0.38
Domestic Land Market Leakage, L^{DA}	-0.08	0.02	-0.22	-0.20	-0.05
World Land Market Leakage , L^{WA}	0.66	0.70	0.62	0.39	1.04
Domestic Fuel Market Leakage, L^{DF}	0.22	0.17	0.26	0.22	0.22
World Fuel Market Leakage, L^{WF}	0.29	0.30	0.29	0.29	0.29
RFS (VEETC Swapped)					
Baseline Ethanol Consumption (billion liters)	43.9	41.9	47.3	43.9	43.9
Change in Ethanol Consumption	5.8	7.8	2.3	5.8	5.8
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.79	-0.43	-2.51	-1.23	0.07
Intended Savings, I	0.83	0.83	0.83	0.88	0.38
Domestic Land Market Leakage, L^{DA}	-0.08	0.02	-0.22	-0.20	-0.05
World Land Market Leakage , L^{WA}	0.67	0.70	0.65	0.39	1.05
Domestic Fuel Market Leakage, L^{DF}	-1.05	-0.78	-2.94	-1.05	-1.05
World Fuel Market Leakage, L^{WF}	0.50	0.46	0.82	0.50	0.50

Notes: The low and high cases for the elasticity of crop demand for food production are constructed by doubling and halving the elasticities of substitution in equation (A.14). Low agriculture and land use emissions case sets all emissions factors to low values, and lowers the world land use conversion ratios by 20%. High agriculture and land use emissions case sets all emissions factors to high values and increases the world land use conversion ratios by 20%.

Table A.18—: Emissions in 2015 Under Alternative Ethanol Production Assumptions

Corn Required for Ethanol Production Energy Required for Ethanol Production	Central Central	Central Low	Central High	Low Central	High Central	Low Low	High High
RFS (VEETC Renewed)							
Baseline Ethanol Consumption (billion liters)	45.4	46.5	44.3	51.3	40.3	52.4	39.2
Change in Ethanol Consumption	11.4	10.3	12.6	5.5	16.6	4.4	17.6
Net Change in Emissions (kgCO_2e per liter ethanol added)	0.40	0.37	0.42	0.61	0.36	0.72	0.40
Intended Savings, I	0.85	0.91	0.80	0.88	0.82	0.94	0.76
Domestic Land Market Leakage, L^{DA}	-0.07	-0.05	-0.09	0.01	-0.10	0.07	-0.11
World Land Market Leakage , L^{WA}	0.79	0.80	0.78	0.90	0.80	0.99	0.79
Domestic Fuel Market Leakage, L^{DF}	0.22	0.22	0.22	0.28	0.15	0.30	0.16
World Fuel Market Leakage, L^{WF}	0.31	0.31	0.31	0.30	0.32	0.30	0.32
RFS (VEETC Swapped)							
Baseline Ethanol Consumption (billion liters)	45.4	46.5	44.3	51.3	40.3	52.4	39.2
Change in Ethanol Consumption	11.1	10.0	12.2	5.2	16.2	4.1	17.3
Net Change in Emissions (kgCO_2e per liter ethanol added)	-0.18	-0.26	-0.10	-0.60	-0.04	-0.80	0.03
Intended Savings, I	0.85	0.91	0.80	0.88	0.82	0.94	0.76
Domestic Land Market Leakage, L^{DA}	-0.07	-0.05	-0.09	0.02	-0.10	0.09	-0.11
World Land Market Leakage , L^{WA}	0.80	0.81	0.79	0.93	0.80	1.04	0.80
Domestic Fuel Market Leakage, L^{DF}	-0.49	-0.56	-0.42	-1.22	-0.33	-1.62	-0.30
World Fuel Market Leakage, L^{WF}	0.43	0.44	0.42	0.56	0.40	0.63	0.40

Notes: Corn for ethanol production analysis varies $\lambda_{E,Y}$ in equation (A.10). Low case assumes that 5% less corn is required per liter than central case in 2015. High case assumes that there is no improvement in corn required per unit ethanol between 2003 and 2015. Energy required for ethanol production analysis varies $\lambda_{E,L}$ in equation (A.10) and the emissions factor ϕ_E. The sensitivity cases adjust labor that is required per liter ethanol of the central case in 2015 to reflect a 10% increase and decrease in energy use. ϕ_E is scaled proportionally to this change in energy use.