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Title: Marginal Emissions from Expansions in Clean Technology are Non-Constant and Policy Dependent – Implications for Mitigation Pledges

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This appendix contains additional simulation results (Section 1), a description of the conceptual framework and the derivation of the marginal emissions formulas (Section 2), and a full exposition of the numerical model. Section 3 lays out the structure of the simulation model. Sections 4 through 6 provide details on parameter values and data used for calibration, the emissions calculations, and the dynamic assumptions that underlie the baseline simulation.

1 Additional Results

Figure 1 presents the impact of the policies on crop prices and the allocation of land. The top panels of Figure 1 report the value of crop production per hectare as a proxy for crop prices. Figure 2 presents the impact of the blend mandate and subsidy on the prices of blended fuel, ethanol and gasoline and the resulting displacement ratio. In the case of the subsidy, the changes in the prices of ethanol, gasoline and blended fuel are the same for each additional unit of gasoline, so these curves lie on top of each other.

Table 1 illustrates that emissions estimates that assume policy-invariant or constant marginal emissions factors can greatly misrepresent the total change in emissions from a non-marginal increase in ethanol.

2 Conceptual Framework

A simple model demonstrates how marginal emissions due to an expansion in a clean technology can be decomposed into substitution and output effects and the factors that determine these two effects. Consider a clean technology (C), a dirty technology (D), and a final consumption good F. The clean and dirty technologies have upward sloping supply curves given by $C(P_C)$ and $D(P_D)$, where P_C and P_D are the prices of the two technologies. The clean and dirty technologies are perfect substitutes in the production of a consumption good: $F = C + D$. Demand for the consumption good is given by a downward sloping demand function $F(P_F)$, where P_F is the price of the consumption good. The marginal greenhouse gas emissions released by the two technologies are ϕ_C and ϕ_D, with $\phi_C < \phi_D$. The ϕ's include all emissions associated with the production and use of the clean and dirty technologies, either directly through flows of energy and material, or indirectly through market adjustments. Total emissions are therefore $E = \phi_C C + \phi_D D$.

The regulator seeks reduce emissions by increasing the quantity of the clean technology using either a subsidy or a blend mandate for the use of the clean technology in the production of the consumption good.

Since production of the consumption good is constant returns to scale, the producer chooses the share of clean technology in the consumption good, θ_C, to minimize the per unit production costs:

$$\begin{aligned} P_F = & \min_{\theta_C} (P_C - s)\theta_C + P_C(1-\theta_C) \\ & \text{s.t.} \quad \theta_C \geq \hat{\theta} \end{aligned} \tag{1}$$

where s is the subsidy for clean technology and $\hat{\theta}$ is the mandated share of clean technology.

The market clearing conditions are:

$$\begin{aligned} C(P_C) &= \theta_C F(P_F) \\ D(P_D) &= (1-\theta_C)F(P_F). \end{aligned} \tag{2}$$

The change in emissions associated with a marginal change in the clean technology is:

$$\frac{dE}{dC} = (\phi_C - \phi_D) + (1 - DR)\,\phi_D \tag{3}$$

where $DR = -\frac{dD}{dC}$ is the quantity of dirty technology displaced by the clean technology, or the "displacement ratio". The first term in equation 3 is the *substitution effect*, which is the difference between the marginal emissions of the clean and dirty technologies. The second term is the *output effect*, which is the difference between one and the displacement ratio multiplied by the marginal emissions of the dirty technology.

The displacement ratio depends on the policy inducing the change in the clean technology:

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\begin{aligned}
DR_{\bar{\theta}} &= 1 - \left(\frac{\eta_F}{1+\eta_F}\right)\left(\frac{\left(\frac{1+\eta_C}{\eta_C}\right)P_C - \left(\frac{1+\eta_D}{\eta_D}\right)P_D}{P_F - \left(\frac{\eta_F}{1+\eta_F}\right)\left(\frac{1+\eta_D}{\eta_D}\right)P_D}\right) \\
DR_s &= 1 - \frac{\eta_F}{\eta_F - \eta_D(1-\theta)}
\end{aligned}
\tag{4}
$$

where η_C and η_D are the elasticities of supply of the clean and dirty technologies and η_F is the elasticity of demand for the consumer good.

Analytical Results

The three insights we highlight in the text are clearly illustrated by equations (3) and (4). First, the substitution effect depends only on the marginal emissions of the two technologies, and therefore does not differ by policy. Second, the output effects differ across policies because policies imply different displacement ratios. Finally, the mandate implies a relationship between the substitution effect and the output effect that is absent for the subsidy. The supply elasticity of the clean technology enters the formula for the displacement ratio of the mandate but not the subsidy. This establishes a link between the substitution and output effects because changes in economic conditions in the market for the clean good may affect both the supply elasticity and marginal emissions of the clean good.

3 Numerical Model

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

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

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

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

The household's budget constraint is given by:

$$P_F F + P_X X + C + H = \bar{L} + \pi_{\bar{A}} + GOV + T \tag{6}$$

where P_F is the price of blended fuel and P_X is the price of food, $\pi_{\bar{A}}$ is the net returns to the land endowment, GOV is a government transfer and T is the terms-of-trade balance (value of crop exports sold less crude oil imports purchased). The wage rate is normalized to one.[1] The household chooses F, M, and C and H to maximize utility (5) subject to (6). The solutions to the resulting first-order conditions yield the uncompensated demand functions

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

for blended fuel, food, the composite good and expenditures on driving.

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

$$F(G, E) = G + 0.66E \tag{7}$$

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

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

$$E \geq \theta F \tag{8}$$

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

The VEETC, denoted τ, is modeled a subsidy for ethanol. The fuel blender chooses E

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[2] Our specification implicitly imposes an efficient RIN market that closes each year (see Bento et al. (2015)).

and G to minimize production costs:

$$P_G G + (P_E - \tau)E \tag{9}$$

subject to equation (7) and (8), where P_G and P_E are the prices of gasoline and ethanol respectively. The resulting factor demand functions for gasoline and ethanol, and the price of blended fuel, are functions of the prices of gasoline and ethanol, the share mandate, and the VEETC.

Ethanol is produced according to a Leontief production function:

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

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

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

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

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

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

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

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

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

$$\text{subject to:}$$

$$\sum_i A_i \leq \bar{A} \tag{12}$$

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

For crops, the functions $y_i(A_i)$ represent yields; for CRP $y_i(A_i)$ represents the per unit land CRP rental payment in dollars. The yield (payment) functions in (12) are assumed to be linear and decreasing in the quantity of land allocated to each land use (A_i):

$$y_i(A_i) = \beta_i - \delta_i A_i \tag{13}$$

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

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

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

The first-order conditions of (12) provide the crop supply functions, $Y(\cdot)$ and $Z(\cdot)$, and the optimal allocation of land to crops and CRP. Only corn is used to produce ethanol, while corn, soybeans, hay and wheat are used in food production. Corn, soybeans, wheat and cotton can be exported.

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

$$\begin{aligned} X(Y_i, L_X) &= \gamma_X \left[\alpha_X L_X^{\frac{\sigma_X - 1}{\sigma_X}} + (1 - \alpha_X)\, Q(\cdot)^{\frac{\sigma_X - 1}{\sigma_X}} \right]^{\frac{\sigma_X}{\sigma_X - 1}} \\ Q(Y_X, Z_X) &= \gamma_Q \left[\alpha_{Z2} Z_{X,2}{}^{\frac{\sigma_Q - 1}{\sigma_Q}} + \alpha_{Z3} Z_{X,3}{}^{\frac{\sigma_Q - 1}{\sigma_Q}} + (1 - \alpha_{Z2} - \alpha_{Z3})\, V(\cdot)^{\frac{\sigma_Q - 1}{\sigma_Q}} \right]^{\frac{\sigma_Q}{\sigma_Q - 1}} \\ V(Y_X, Z_{X,1}) &= \gamma_V \left[\alpha_V Y_X{}^{\frac{\sigma_V - 1}{\sigma_V}} + (1 - \alpha_V)\, Z_{X,1}{}^{\frac{\sigma_V - 1}{\sigma_V}} \right]^{\frac{\sigma_V}{\sigma_V - 1}} \end{aligned} \tag{14}$$

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

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

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

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

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

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

$$\begin{aligned} P_Y &= \gamma_i \left(Y_W\right)^{\frac{1}{\eta_Y}} \\ P_Z &= \gamma_i \left(Z_W\right)^{\frac{1}{\eta_Z}} \end{aligned} \tag{15}$$

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

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

$$P_R = \gamma_R \left(R\right)^{\frac{1}{\eta_R}} \tag{16}$$

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

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

$$t_F F + t_L \bar{L} = GOV + y_N(A_N)A_N + \tau E. \tag{17}$$

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

$$\begin{aligned} Y &= Y_X + Y_E + Y_W \\ Z &= Z_X + Z_W \\ R &= R_G \end{aligned} \tag{18}$$

the labor market in the US clear and the government budget (17) is balanced. The terms-of-trade balance in (6) is given by:

$$T = \sum_i \int_{P_i^0}^{P_i^1} Y_{i,W}(P_i)dP_i - \int_{P_R^0}^{P_R^1} R(P_R)dP_R \tag{19}$$

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

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

$$GHG = \phi_G G + \phi_E E + \phi_Y A_Y + \phi_Z A_Z + \phi_{N,D} A_{N,D} + \phi_{N,W} A_{N,W} + \phi_R R_W \tag{20}$$

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

4 Data and Calibration

Benchmark Economy Table 2 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. Table 3 presents key parameter values used in calibration.

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.[8] 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 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.[9] 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

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

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

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.[10] 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 (5), of 0.50, between food and the composite good, σ_W in (5), of 0.09, and between fuel and non-fuel expenditures on driving, σ_M in (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 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

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[10] 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.

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.[11] 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 biofuel policies. [12]

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.

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[11] 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.

[12] 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.

Gasoline Production We assume an elasticity of substitution between crude oil and labor in the production of gasoline, σ_P, of 0.06. This was selected to approximate a perfectly complementary relationship between crude oil and labor in the production of gasoline.

The price of gasoline faced by the fuel blender is calibrated to the average spot price for conventional, regular grade gasoline in 2003.[13]

Ethanol Production The per unit ethanol input requirements in equation (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 (2010b).

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

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

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

Transportation costs incurred by the ethanol producer are also accounted for. First, we assume that the cost of shipping ethanol to its final destination is incurred by the ethanol producer. The cost of shipping ethanol is \$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 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

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

assume that 30% of co-products are transported locally at zero cost to the ethanol plant.[15]

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 (14)) are provided in Table 3. 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*).

Land Use Allocation To construct the per-unit land labor expenditures for agricultural production, l_i, we sum expenditures over four broad input categories: labor, capital, energy and fertilizer (Table 5). 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

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

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.[16] Second, expenditures on other variable inputs are from the CCR.[17] Fertilizer expenditures are disaggregated in the lower panel of Table 5.

Land Supply Elasticities The six δ_i in (13) are taken from Bento et al. (2015). These were estimated in order to match the supply response of the US land market for each year that the model is run, using the literature elasticities reported in Table 4 as inputs. This estimation strategy provides two main benefits. First, it ensures proper calculation of the counterfactual amount of ethanol that would be produced in the absence of various biofuel policies. Second, it allows for the proper calculation of the domestic emissions from agricultural and land use adjustments.[18] For 2003, the six β_i in (13) were chosen to match the yields reported in Table 2. For later years, each β_i is adjusted given exogenous growth in crop yields.

Rest-of-world Crude Market The model framework presented above considers the excess supply of crude oil going to the US for gasoline consumption, R. To calibrate the

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

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

[18] Refer to Bento et al. (2015) for a detailed exposition of our estimation strategy, as well details on model validation given this approach.

elasticity of excess supply facing US gasoline producers and to calculate the impact of biofuel policies 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 emissions channels.[19]

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

$$R = D_{Gas}^{US} = S_{Crude}^{ROW} + S_{Crude}^{US} - D_{Crude}^{ROW} - D_{Dist}^{US} - D_{Other}^{US} \tag{21}$$

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

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

$$\begin{aligned}\eta_R = \eta_{S,Crude}^{ROW}\left(\frac{S_{Crude}^{ROW}}{D_{Gas}^{US}}\right) + \eta_{S,Crude}^{US}\left(\frac{S_{Crude}^{US}}{D_{Gas}^{US}}\right)& \\ - \eta_{D,Crude}^{ROW}\left(\frac{D_{Crude}^{ROW}}{D_{Gas}^{US}}\right) - \eta_{D,Dist}^{US}\left(\frac{D_{Dist}^{US}}{D_{Gas}^{US}}\right) &- \eta_{D,Other}^{US}\left(\frac{D_{Other}^{US}}{D_{Gas}^{US}}\right).\end{aligned} \tag{22}$$

To calibrate η_R using (22) 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,

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

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

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 6. In 2003, total world crude considered in our framework is 4,545.8 billion liters (28,954 million barrels). [21] The rest of the world is the primary supplier of crude oil, contributing 4,046.2 billion liters while the US supplies 499.6 billion liters. On the demand side, ROW crude demand totals 3,419.5 billion liters. US crude oil demand makes up the remainder, with roughly 44% (490.3 billion liters) of total US crude oil demand going to gasoline production.

The final column in Table 6 reports the central literature values for the elasticities on the right-hand side of (22) 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

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[21] Our estimate here is slightly below (138 million barrels) the EIA estimate of total world crude consumption because we ignore gasoline used for non-transportation purposes in the US. Keeping the market shares constant, we adjust the total size of the crude market to reflect this difference. As a result, the quantities reported in Table 6 will be slightly below the values reported by the EIA.

the range of -0.02 to -0.06 (Krichene, 2002, 2005; OECD, 2004; Gately, 1984; Gately and Huntington, 2002). In our model, the elasticity of ROW crude demand is used to calculate the change in rest of world crude oil use. A number of studies (Gately and Huntington (2002); Dargay and Gately (1995, 2010)) have noted that the demand response for crude products to changes in crude prices, particularly in developed countries, is more limited for price decreases than price increases. Since biofuel policies 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 (16) to reflect an excess supply elasticity for crude oil of 0.5 in our central case.

Two considerations are important for comparing our crude oil elasticities to other biofuel studies. First, our model measures the annual impact of biofuel policies 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 policies 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 (15), 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:

$$\gamma_{ROW,i} = \frac{-\eta_{S,i}^{ROW} S_i}{\eta_{D,i}^{ROW} D_i - \eta_{S,i}^{ROW} S_i} \tag{23}$$

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 (2010b).[22] More recent studies, such as Hertel et al. (2010), argue that the earlier analyses overestimate world land use change because they fail to account for factors that may mitigate a portion of the expansion in world agricultural production such as price induced yield improvements and crop demand adjustments.

5 Emissions Calculations

The emissions factors corresponding to the ϕ terms in the emissions equations are presented in Table 7 and are described in detail below. For each product or activity, we account for the

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

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).[23] For all emissions factors, we abstract from infrastructure related emissions. For example, we measure the emissions from the operation of an ethanol production facility, but do not include emissions from the construction of, or the raw materials used to construct, the facility itself. As a result, our emissions system boundary is slightly more restrictive than that of earlier lifecycle analyses (see for example, Farrell et al. (2006); Hill et al. (2006)), but consistent with the US EPA (2010b).

Overview The 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 as on-farm emissions.[24] 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

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

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

example EPA (2010b), Searchinger et al. (2008) and Fargione et al. (2008)).

Gasoline The lifecycle emissions of gasoline, ϕ_G, are 3.0 kgCO$_2$e/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$_2$e/liter. This factor assumes a representative natural gas fired dry-mill ethanol plant, consistent with the US (EPA, 2010b). We also account for the release of CH_4 and N_2O from ethanol combustion, which totals 0.02 kgCO$_2$e/liter (EPA, 2010b).[25] Combining, ϕ_E is 0.62 kgCO$_2$e/liter.

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

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 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

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[25] 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.

other miscellaneous products). We are therefore considering emissions from approximately 47% of the world crude oil market.[26] 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 US biofuel policies. This assumption is discussed in detail in Bento et al. (2015).

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 shares of these fuels in 2003. The market shares for gasoline (32%) and distillate fuels (68%) are calculated using data from the EIA's International Energy Statistics. The emissions factor for crude used for gasoline production in the rest of the world is 2.4 $kgCO_2e$/liter (374.2 $kgCO_2e$/barrel). The emissions factor for distillate fuels is slightly higher 2.7 $kgCO_2e$/liter (426.3 $kgCO_2e$/barrel).

Agricultural Production To construct ϕ_Y and ϕ_Z we consider on-farm sources of emissions, which include agricultural N_2O and emissions from energy use and liming, as well as emissions from agricultural input production. In our central case, N_2O emissions from agricultural production are calculated using methods and default parameters from the

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[26] 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.

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).

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

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[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).

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.[28]

Domestic Land Use Change We assume that the emissions from converting land held in CRP to cropland, $\phi_{N,D}$, are 2.3 mgCO_2e/ha. To calculate this factor we assume, following the EPA (2010b), that the conversion of CRP land to cropland results in the immediate release of all carbon stored in the above-ground biomass on CRP land. In addition, the carbon stored in below-ground biomass and soils of CRP land is released within the next 30 years. Consistent with standard practice (see EPA (2010b)), we amortize total emissions from land use conversion over 30 years, with no discounting.[29] 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.

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, 2010b). The emissions from world land use change are substantially larger than the emissions from

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[28] 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.

[29] 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.

domestic land use change. This is because cropland expansion in the rest of the world is predicted to displace previously undisturbed land cover with large carbon stocks. The international land use change emissions factors are derived from economic models used by the US EPA that predict the location (54 regions) and type (pasture, native ecosystems) of land converted to cropland as a result of the RFS for corn ethanol (EPA, 2010b).[30] 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.

6 Intertemporal Dynamics

To establish a baseline in 2015, 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 could alter the 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.[31]

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,

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

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

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 (16).

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.

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

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

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Figure 1: Impacts of Policies on Land Markets

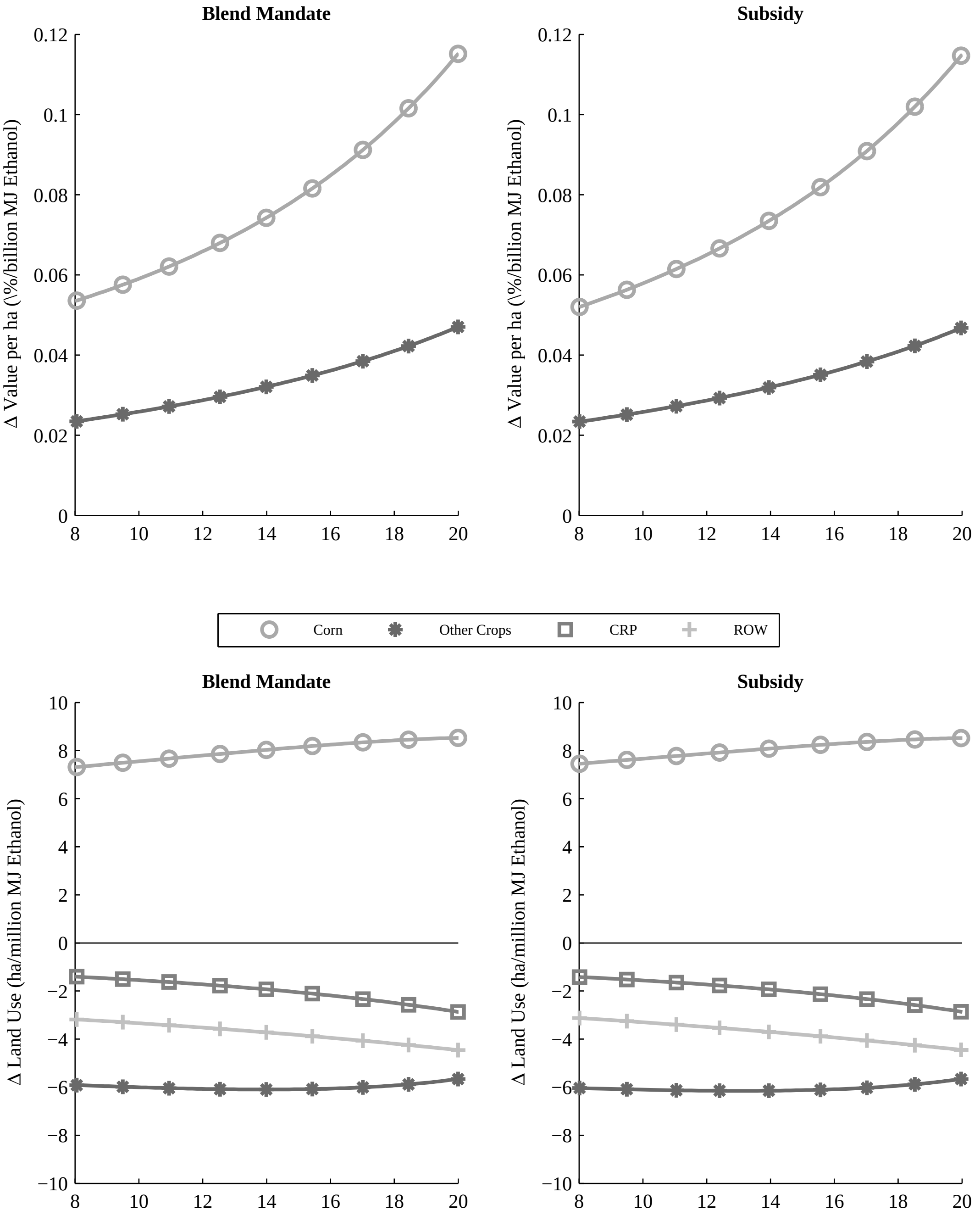

Figure 2: Impacts of Policies on Fuel Markets

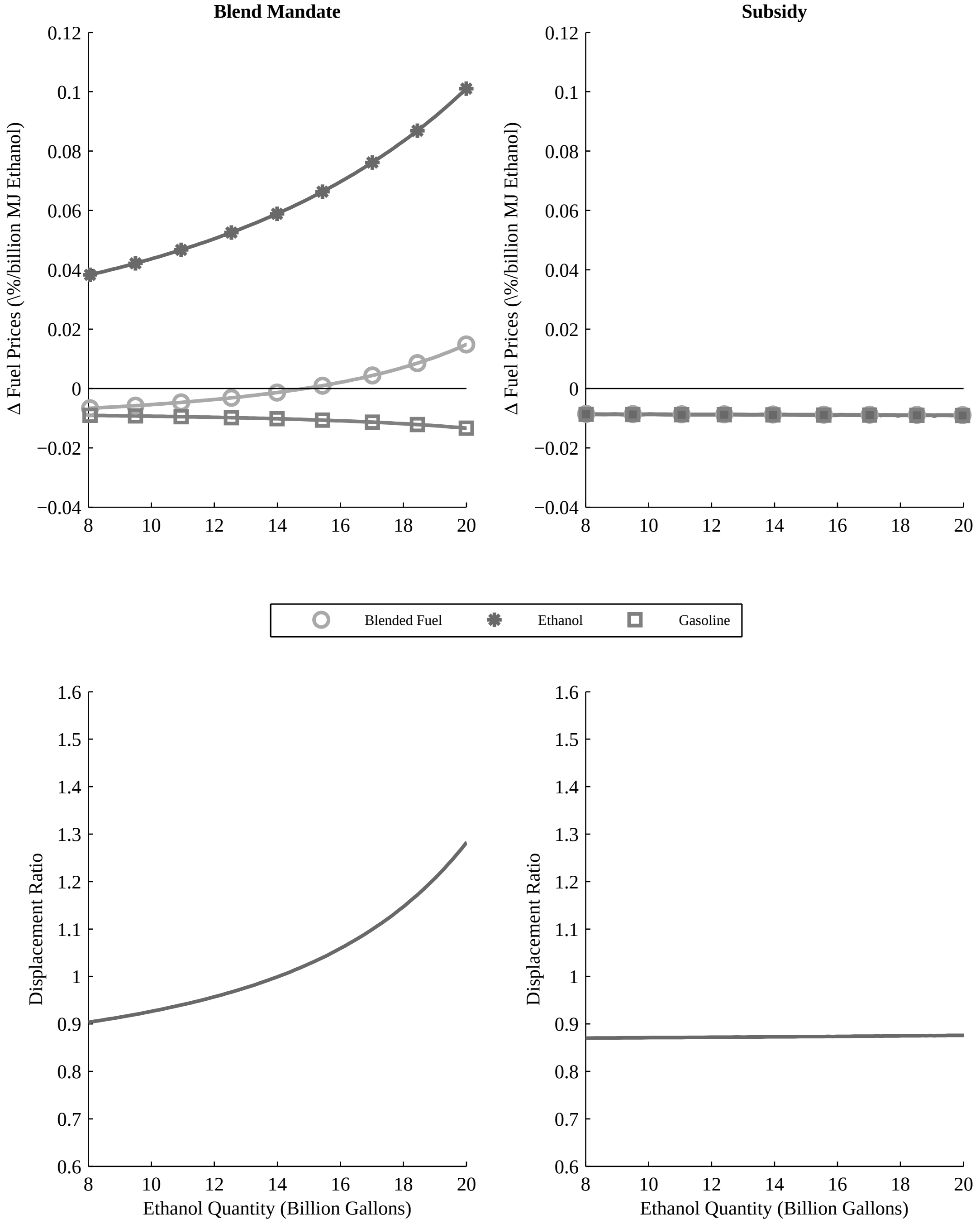

Table 1: Implications of Non-Constant Marginal Emissions

		Constant Marginal	
	Actual	First	Last
9 Billion Gallon Baseline			
3 Billion Change	0.4 (21.3)	0.3 (21.0)	0.4 (21.7)
6 Billion Change	0.6 (43.1)	0.6 (41.9)	0.1 (43.4)
14 Billion Gallon Baseline			
3 Billion Change	-0.1 (22.2)	0.2 (21.7)	-0.6 (23.7)
6 Billion Change	-1.7 (49.9)	0.4 (43.5)	-5.8 (65.7)

		Constant Marginal	
	Actual	First	Last
9 Billion Gallon Baseline			
3 Billion Change	1.6 (22.6)	1.2 (21.8)	2.0 (23.5)
6 Billion Change	4.1 (47.1)	2.4 (43.6)	6.0 (51.2)
14 Billion Gallon Baseline			
3 Billion Change	3.2 (25.9)	2.7 (24.9)	3.7 (27.1)
6 Billion Change	7.4 (54.2)	5.3 (49.7)	9.7 (58.7)

Values in parenthesis represent uncertainty, the difference between highest and lowest value across all parameter cases, corresponding to each central value.

Table 2: 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	$1,036.32	NASS
Fuel Quantities		
VMT (trillion passenger miles)	2.69	FHWA
Blended Fuel (billion liters)	499.97	
Ethanol (billion liters)	10.39	FHWA
Regular Gasoline (billion liters)	490.28	FHWA
Domestic Crude Oil (billion barrels)	3.12	EIA
Fuel Prices		
VMT ($/passenger mile)	$0.19	
Blended Fuel ($/liter)	$0.41	
Ethanol ($/liter)	$0.35	
Regular Gasoline ($/liter)	$0.23	EIA
Crude Oil ($/liter)	$0.18	EIA
Labor Tax Rate (%)	36.59%	
Fuel Tax ($/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 3: Calibration Parameter Values

Parameter	Value	Source
Households		See page 12
Elasticity of substitution, Consumer, σ_U	0.5	
Elasticity of substitution, Consumer, σ_W	0.09	
Expenditure Share on Food	0.035	
Expenditure Share on VMT	0.065	
Elasticity of substitution, VMT, σ_M	0.21	
Ratio of fuel cost to total cost of driving	0.4	
Initial Fuel Economy (km/liter)	8.7	FHWA
Ethanol		
kilograms corn required per liter ethanol, λ_{E,Y_1}	2.56	Wang (2009)
Labor expenditures per liter ethanol	\$0.13	Farrell et al. (2006)
Average tariff rate (plus fuel surcharge) per liter of ethanol	\$0.02	See page 14
Gasoline and Crude Oil		
Elasticity of substitution, Regular Gasoline Production, σ_P	0.06	See page 14
Share of crude oil cost to total cost of gasoline per liter	0.61	EIA
Crude oil yield for gasoline	0.47	EIA
Own price elasticity of crude oil supply	0.50	See page 17
Food Production		See page 16
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	
Crop Export Markets		See page 20
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

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

Table 4: 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 5: 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 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 (22). 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 7: Final Product/Activity Emissions Factors

	Central	Source
Gasoline (gCO_2e/MJ)	93.0	
Combustion	75.1 -	EPA (2010b)
Production	18.9	EPA (2010b)
Ethanol (gCO_2e/MJ)	27.4	
Combustion	0.8	EPA (2010b)
Production	26.6	EPA (2010b)
Crude Oil ($kgCO_2e$/liter)	2.6	EPA (2011)
Agriculture ($MgCO_2e$/ha/year)		
Corn	3.2	
Soybeans	0.5	
Hay	1.3	
Wheat	1.0	
Cotton	1.4	
Land Use Change ($MgCO_2e$/ha/year)		
CRP	2.3	Fargione et al. (2008)
Rest of World	8.0	EPA (2010b)

Notes: 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.