Implications of market-mediated emissions and uncertainty for biofuel policies

— Supporting Information —

This document describes the mathematical model used in the analysis, provides more details of the Monte Carlo simulation, and provides additional figures referred to in the main text.

S-1 Mathematical model

We analyze the impact of biofuels on the world market for oil and oil products in a static framework. We divide the world into two regions—home and rest of the world (ROW), with home as the policy implementing region. We assume an open economy and competitive markets in both regions. We consider three broad types of fuels, namely, crude oil, oil products and renewable liquid fuels. We classify crude oil as conventional crude (CC) oil and synthetic crude oil from oilsands (OS) in Canada. The two types of crude oil are considered perfect substitutes that differ only in their global warming intensity GWI. OS requires more energy for processing the primary feedstock; its GWI is reported to be 10% to 20% higher than that of CC (Brandt, 2012). We model three types of oil products, namely, gasoline, diesel and an aggregate representing the rest of the products of oil refining. The GWI intensity of each oil product while different is also assumed to vary depending on whether they are derived from CC or OS. The oil refining process is assumed as Leontief type, i.e., the relationship between inputs and outputs in the process is one of fixed proportion. We analyze the sensitivity to alternative values of these fixed proportions.

The model includes two biofuels, corn ethanol and sugarcane ethanol, which are considered perfect substitutes. Gasoline and ethanol are also considered as substitutes on an energy-equivalent basis but only up to a limit, commonly referred to as the “blend wall”, which represents an upper bound on the fraction of ethanol blended with the gasoline used in conventional gasoline automobiles. The GWI of each type of ethanol is represented as the sum of two quantities: (i) the
direct life cycle emission intensity, which represents emissions traceable to the processes involved in the production and use of biofuel, and (ii) emission from indirect land use change (ILUC). The GWI rating of each crude oil and oil product pathway is defined by a single value representing the pathway’s life cycle CO$_2$e emissions.

We model three broad types of policies, namely, biofuel share mandate, emission intensity standard and fuel carbon tax. The biofuel share mandate is a policy that specifies the minimum share, by volume, of ethanol in domestic gasoline consumption. The emission intensity standard regulation specifies a maximum average fuel GWI for the home region. Under this policy, each distinct combination of feedstock and fuel production process is assigned a “nominal” GWI rating that is used to determine compliance with the regulation. The third type of policy is an exogenous carbon tax on fuel life cycle GHG emissions. We describe the mathematical formulation of these policies next.

We use the following notation. Let superscripts $h$, $a$, and $w$ denote the home, ROW, and the world, respectively. Let subscripts, $o$, $cc$, $os$, $g$, $d$, $x$, $ce$, and $se$ denote oil, conventional crude oil, oilsands, gasoline, diesel, rest of oil products, corn ethanol, and sugarcane ethanol respectively. Let $gcc$ and $gos$ denote gasoline from conventional crude oil and gasoline from oilsands respectively. Let $R = \{h, a\}$ denote the set of regions, $G = \{gcc, gos, ce, se\}$ the set of gasoline substitutes, $F = \{gcc, gos\}$ the set of gasoline from the two different types of oil, $B = \{ce, se\}$ the set of biofuels. Let $p$ denote the fuel price, $q$ the quantity of fuel, $z$ the lifecycle GHG intensity of fuel, and $Z$, GHG emissions. $\eta$ is a constant which represents the ratio of energy density of ethanol to the energy density of gasoline and $\alpha_{max}$ denote the blend wall, i.e., the maximum feasible volume share of ethanol in the home region’s consumption of ethanol blended gasoline. Let $D$ and $D^{-1}$ denote the demand and inverse demand functions respectively. Let $S$ and $S^{-1}$ denote fuel supply function and the inverse supply function, respectively. We assume that the functions are well-behaved and that the inverse function exists. Transportation costs are assumed to be a negligibly small component of the price of fuel, and hence, set to zero. We assume that blending of fossil fuel and renewable fuel is costless.

We model three types of policies implemented in the home region: (i) a fuel GHG tax, $t$; (ii) a renewable fuel share mandate(SM), $\alpha_{SM}$; (iii) an emission intensity standard (ES) (a policy akin to the low-carbon fuel standard), which establishes an upper-bound on the average GHG intensity of fuel used within a region, $z_{ES}$. We allow for the ability to analyze the above policies in the presence of a subsidy, $s$, tariff on ethanol imports, $\tau$. We describe the system of equations describing the equilibrium under each policy below.
Renewable fuel volumetric mandate ($\alpha_{SM}$): Under this policy, the total quantity of renewable fuel consumed within the home region is such that its share in total fuel consumption is not less than $\alpha_{SM}$. The system of equations describing the equilibrium under an SM are:

Home ethanol mandate constraint

$$\alpha_{SM}^h \leq \alpha \leq \alpha_{max}^h, \text{ where } \alpha = \frac{\sum_{b \in B} q_b^h}{\sum_{f \in F} q_f^h + \eta \sum_{b \in B} q_b^h} \quad (1a)$$

Ethanol blending condition

$$p_{gb}^h \leq (1 - \alpha)p_g + \alpha(p_b - s_b^h + \tau_b^h), \forall b \in B \quad (1b)$$

Biofuel price

$$\frac{p_b}{\eta} \geq p_g, \forall b \in B \quad (1c)$$

Biofuel supply

$$p_b \leq S_b \left( \sum_{r \in R} q_r^b \right), \forall b \in B \quad (1d)$$

Home gasoline demand

$$\sum_{f \in F} q_f^h + \eta \sum_{b \in B} q_b^h = D^h_g(p_{gb}^h + t_g^h) \quad (1e)$$

ROW gasoline demand

$$\sum_{f \in F} q_f^a + \eta \sum_{b \in B} q_b^a = D^a_g(p_g + t_g^a) \quad (1f)$$

Quantity of gasoline supplied as a fixed proportion of total quantity of crude oil

$$q_g^h + q_g^a = \beta_g q_o \quad (1g)$$

Quantity of diesel supplied as a fixed proportion of total quantity of crude oil

$$q_d = \beta_d q_o \quad (1h)$$

Quantity of other oil products supplied as a fixed proportion of total quantity of crude oil

$$q_x = \beta_x q_o \quad (1i)$$
Diesel demand

\[ D^h_d(p_d + t^h_d) + D^a_d(p_d + t^a_d) = q_d \]  \hspace{1cm} (1j)

Other oil products demand

\[ D^h_x(p_x + t^h_x) + D^a_x(p_x + t^a_x) = q_x \]  \hspace{1cm} (1k)

Zero oil refining profit condition

\[ \beta_g p_g + \beta_d p_d + \beta_x p_x = p_o \]  \hspace{1cm} (1l)

Oil supply

\[ q_o = S^h_o(p_o) + S^a_o(p_o), \text{ where } S^r_o = S^c_r + S^r_o \forall r \in R \]  \hspace{1cm} (1m)

ROW ethanol constraint

\[ \frac{\sum_{b \in B} q^a_b}{\sum_{f \in F} q^a_f + \eta \sum_{b \in B} q^a_b} = \alpha^o_0 \]  \hspace{1cm} (1n)

Equation (1a) is the constraint on the volume share of ethanol in the home region under the policy. The upper limit on this share is the ethanol blend wall, \( \alpha_{max} \).

Equation (1b) represents the competitive-blending condition under the ethanol share mandate for each pair of renewable fuel and fossil fuel. The equality holds when \( q^h_b > 0 \) else the inequality applies. The left hand side cannot be greater than the right hand side for it would imply there are positive profits in blending biofuel \( b \) with gasoline, which cannot be an equilibrium.

Equation (1c) is a condition which says that if a given type of ethanol is consumed in abroad, then the price of biofuel equals the world price of gasoline. Since there is no biofuel policy in the rest of the world, biofuels compete with gasoline in a free market. Therefore the price of biofuel (adjusted for energy equivalence) equals the price of gasoline in the rest of the world whenever a positive amount of a biofuel is consumed.

Equation (1d) is the supply equation for biofuel which says that the energy equivalent price of biofuel is equal to or greater than the price of gasoline. The left hand side cannot be less than zero in equilibrium else it would suggest ethanol is cheaper compared to gasoline.

Equation (1e) represents the demand for gasoline in the home region, which is function of the consumer price of blended gasoline, \( p_{gb} \).

Equation (1f) represents the demand for gasoline in the ROW.

Equation (1g) relates the global gasoline consumption, \( q^h_g + q^a_g \), to the quantity of gasoline derived from refining of crude oil, which is a fixed proportion \( \beta_g \) of crude oil.

Equation (1h) relates the global diesel consumption, \( q_d \), to the quantity of diesel derived from refining of crude oil, which is a fixed proportion \( \beta_d \) of crude oil.
Equation (1i) relates the global consumption of rest of oil products, $q_x$, to the quantity of these products derived from refining of crude oil, which is a fixed proportion $\beta_x$ of crude oil.

Equation (1j) relates the global diesel consumption to demand function for diesel in the two regions.

Equation (1k) relates the global consumption of rest of oil products to demand function for these products in the two regions.

Equation (1l) is a condition similar to the competitive blending condition, which says that in equilibrium there is zero profits in oil refining.

Equation (1m) relates the global oil consumption to the global oil supply, which is the sum of oil supply from region.

Equation (1n) is an additional constraint we impose on ethanol consumption in ROW. Our initial simulations without this constraint predicted that ROW ethanol consumption would decline to zero in response to biofuel policies in the home region. The reality however is that there exist ethanol mandates in the ROW, the most important example being the ethanol mandate in Brazil, which ranged between 20% and 25% during 2001 to 2010. We therefore introduced an additional constraint that the share of ethanol in the ROW region does not fall below its level in the baseline, $\alpha_0$. Under the assumption that ROW ethanol consumption is essentially confined to Brazil and that Brazilian fuel consumption is a constant fraction of ROW fuel consumption, a constant share for biofuel in Brazilian fuel consumption translates into a constant share of ethanol in ROW biofuel consumption.

**Emission intensity standard** ($z_{ES}$): Under this regulation, the average GWI rating across all fuel consumed within the policy region cannot exceed the standard, $z_{ES}$. The system of equations describing the equilibrium under an ES are identical to that for the SM with the exception of the first two equations which are shown below.

\[
\text{Emission standard constraint} \quad z = \frac{\sum_{f \in F} z_f q_f^h + \eta \left( \sum_{f \in F} z_b q_b^h \right)}{\sum_{f \in F} q_f^h + \eta \left( \sum_{f \in F} q_b^h \right) \geq z_{ES}} \quad (2a)
\]

\[
\text{Ethanol blending condition} \quad p_{gb}^h \leq ((1 - \alpha_b)p_f + \alpha_b(p_b - s_b^h + \tau_b^h))0, \forall b \in B, f \in F \quad (2b)
\]
Equation (2a) represents the overall constraint on the emission intensity imposed by the ES for the home region. Similar to the SM, equation (2b) represents the competitive-blending condition under the ES for each pair of renewable fuel and fossil fuel. The difference is that the proportion in which the two fuels are blended is specific to each clean fuel and fossil fuel pair, i.e.,

\[ \alpha_b = \frac{z_f - z_b}{z_f - z_b}, \forall b \in B. \]

If ILUC emissions of biofuel are included in the policy GWI rating of biofuels then \( z_b \) represent the sum of both direct life cycle GWI and ILUC GWI else it represents direct life cycle GWI of any given biofuel.

**Fuel carbon tax**\((t)\): The fuel carbon tax denotes a tax on fuel GHG emissions. The system of equations describing the equilibrium under a share mandate or an emission standard with the exception of the first two equations which are shown below.

**Relationship between home motor gasoline price and gasoline price**
\[
p^h \leq p_f + tz_f, \forall f \in F
\]  

**Relationship between home motor gasoline price and biofuel price**
\[
p^h \leq \frac{p_b + tz_b - s_b + \tau_b}{\eta}, \forall b \in B
\]  

Equation 3a expresses the relationship between the world gasoline price, \( p_f \), and the domestic price of motor gasoline \( p^h \). \( tz_f \) is the tax on gasoline in the home region. If \( p^h > p_f + tz_f \), then gasoline suppliers in the home region can earn positive profits, which cannot be an equilibrium. The equality holds whenever a positive amount of gasoline is consumed in the home region. A similar interpretation holds for every other fuel including the biofuels, taking into account subsidies and tariffs as applicable. If ILUC emissions of biofuel are included in the policy GWI rating of biofuels then \( z_b \) represent the sum of both direct life cycle GWI and ILUC GWI else it represents direct life cycle GWI of any given biofuel.

**Solution selection procedure under multiple equilibria** : Since our model is not an optimization model but an equilibrium model with a system of equations, the solution of the system sometimes results in multiple feasible solutions representing multiple equilibria. In such cases, we choose the solution that results in lowest price of fuel or the highest consumer surplus in the home region.
S-2 Functional forms and calibration

We describe briefly the specification of the shape of the supply and demand functions and the procedure for their calibration prior simulating the policy scenarios. All the relevant parameters required for calibration are chosen from within the range listed in Table 1 of the main paper.

We assume a linear function for the supply of conventional crude oil and renewable fuels in each region. Given a price elasticity of supply, $\epsilon^s$ and the price and quantity of a fuel supplied at a given time, $t_0$, a linear supply (or demand) function of the form $q = a + bp$, can be calibrated as follows:

$$b^r_f = \epsilon^r q_{f,0}^r, \forall k \in \{cc, cb, sb\}, \forall r \in R$$  \hspace{1cm} (4)

$$a^r_f = q_{f,0}^r - b^r_f p_{t_0}^r, \forall k \in \{cc, cb, sb\}, \forall r \in R$$  \hspace{1cm} (5)

For oil sands, which comprise a small but a growing share of the oil supply, we assume a hockey-stick shaped supply function. This is chosen so to characterize oil sand production as an industry which faces an almost constant marginal cost up to a capacity that is growing at an exogenous rate each year but fixed in any given year. Therefore, if the world price of oil exceeds the minimum price that will makes oil sands profitable, then oil sand supply occurs close to capacity that year. Mathematically, the hockey-stick shape supply curve can be represented as,

$$p = \beta (\bar{Q} - q)^\alpha + \gamma$$  \hspace{1cm} (6)

Given the capacity for oil sands supply at $t_0$, $Q_{os,t_0}$, the minimum price of oil above which oil sands are produced, $p_{os}$, and the elasticity of supply of oil sands (since the oil sand industry is assumed to be operating close to capacity, this is a small number, less than 0.05), $\epsilon^s_{os}$, we calibrate, $\alpha, \beta$ and $\gamma$ as follows

$$\alpha_{os} = -\frac{\bar{Q}_{os,t_0}/q_{os,t_0} - 1}{\bar{Q}_{os,t_0}}$$  \hspace{1cm} (7)

$$\beta_{os} = \frac{(p_{os} - p_{os})}{(Q_{os,t_0} - Q_{os,t_0})^{\alpha_{os}} - Q_{os,t_0}}$$  \hspace{1cm} (8)

$$\gamma_{os} = p_{os} - \beta_{os} \bar{Q}_{os,t_0}$$  \hspace{1cm} (9)

The cost and capacity constraints were chosen based on projections reported in (Timilsina et al., 2005).

The demand for the different fuels, namely, oil, gasoline, diesel, rest of oil products, is also to be linear in shape, and is calibrated in manner similar to the linear supply function of crude oil and
the biofuels. There is no separate demand function for gasoline and biofuel for these are considered substitutes and hence jointly represented by a single demand function for ethanol blended gasoline, which is also assumed linear.

The supply of gasoline, diesel and the rest of oil products aggregate is assumed to be a fixed proportion of the supply of oil. For gasoline, this is computed as the ratio of world gasoline consumption and world oil consumption in the base year. The computed values for gasoline, diesel and the aggregate of rest of oil products are 0.25, 0.28 and 0.47 respectively.

We assume the base year as the year 2007. For the simulation we assume that conventional crude oil is produced in both the home and ROW regions but oilsands is produced only in the ROW region. We assume that corn ethanol is produced only by the home region, and cane biofuel is produced only by the ROW region. The data for the base year are shown in Table S-1. Figure S-1 shows the calibrated functions at the mean value of each input parameter to our model.

Table S-1: Base year (2007) data used in model calibration. We use data for the US for “home” region. ROW = rest of world. mbpd = million barrels per day.
Figure S-1: Representative supply and demand functions calibrated at mean value of input parameters shown in Table 1 of the main paper.
S-3 Deterministic results

In this section we discuss of the results from a single model run using the mean values for all parameters. We discuss this case only to illustrate the working of the model: it should not be interpreted as a “best” estimate. In any case, the results for this “mean inputs” case are similar to the median values from the Monte Carlo simulations which are described in Section S-4.

Oil consumption in the home region declines under all policies while global GHG emissions increase under some policies and decrease under the others (Figure S-2a). Specifically, both the 10% and 15% biofuel mandates and the 5% emission standard increase emissions. Global biofuel consumption increases under all policies with the exception of carbon tax, driven essentially by an increase in biofuel consumption in the home region (see Figure S-2b). Global ethanol consumption increases with the policy stringency under any given type of policy.

The consumption of any given type of ethanol and consequently its price may however either increase or decrease under a given policy (see Figure S-2c). Ethanol policies increase the demand for ethanol and therefore lower the demand for gasoline, causing the world price of gasoline to decline. As a result, world oil price declines. This leads to a lower production of oil and therefore a lower supply of oil products. With the demand for non-gasoline oil products remaining unchanged, the price of diesel and rest of oil products therefore increase. (see Figure S-2c). Because we hold the relative proportions of the different oil products fixed in our model, we overestimate the magnitudes of reduction in gasoline and oil price and increase in the price of non-gasoline products. Allowing the fixed-proportions to vary in response to price, our model will predict a smaller impact on prices. The price of ethanol blended gasoline at home may either increase or decrease under the different types of policies. However, for any given type of policy, higher stringency increases the price of blended gasoline. With the exception of the carbon tax, the change in oil price is inversely correlated with change in global biofuel use (see Figure S-2b).

The share of ethanol in the home region increases with the stringency under any given type of policy, but the share of any given type of ethanol may increase or decrease (Figure S-2d). As expected, both levels of the volumetric mandates achieve the corresponding target share for all ethanol in the home region. ES-5 achieves a similar share of ethanol as SM-15, but the two policies lead to slightly different shares of corn and cane ethanol, with the ES-5 resulting in a greater share of cane ethanol, attributable to sugarcane ethanol having a lower GWI than does corn ethanol. All emission standards other than ES-5 result in zero corn ethanol use in the home region; all the corn ethanol is now consumed in ROW. Whereas ethanol use approaches the 20% blend wall under ES-ILUC-5, it well exceeds this limit, approaching 30%, under ES-ILUC-10, suggesting that the
policy target of 10% reduction in GWI rating would be infeasible given our assumed fuel ratings.

S-4 Monte Carlo simulation

In this section we provide additional details about the Monte Carlo simulation.

S-4.1 Fuel GWI distributions

We adopt the distributions for direct life cycle CO₂-equivalent GHG emissions from Venkatesh et al. (2011), as shown in Table S-2. Given the right skew represented by these 90% confidence intervals, we assume lognormal distributions.

Table S-2: Global warming intensity of refined petroleum products, g CO₂e MJ⁻¹. Source: Venkatesh et al. (2011) and supplemental data received from the Venkatesh by email.

<table>
<thead>
<tr>
<th>Product</th>
<th>Mean</th>
<th>5th</th>
<th>95th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>89.2</td>
<td>84.8</td>
<td>96.9</td>
</tr>
<tr>
<td>Distillate fuel</td>
<td>93.4</td>
<td>89.5</td>
<td>100.8</td>
</tr>
<tr>
<td>Jet fuels</td>
<td>91.3</td>
<td>87.2</td>
<td>98.8</td>
</tr>
<tr>
<td>Kerosene</td>
<td>91.3</td>
<td>87.2</td>
<td>98.8</td>
</tr>
<tr>
<td>Residual fuel</td>
<td>94.9</td>
<td>88.1</td>
<td>106.8</td>
</tr>
<tr>
<td>LPG</td>
<td>85.8</td>
<td>80.3</td>
<td>98.3</td>
</tr>
<tr>
<td>Fuel coke</td>
<td>144.7</td>
<td>131.4</td>
<td>158.7</td>
</tr>
<tr>
<td>Refinery fuel</td>
<td>85.7</td>
<td>76.2</td>
<td>96.3</td>
</tr>
<tr>
<td>Asphalt/LUB</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Petrochem feedstocks</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Rest of oil products</td>
<td>79.2</td>
<td>75.5</td>
<td>87.6</td>
</tr>
</tbody>
</table>

S-4.2 Effect of including ILUC in the policy GWI rating

Figure S-3 shows difference between ES-ILUC and ES-NoILUC at each stringency level for four variables, namely, global GHG emissions, global oil consumption, home oil consumption and the home price of blended gasoline. For each variable, \( X \), the x-axis represents the difference \( X_{ES-ILUC} - X_{ES-NoILUC} \). The left and right columns shows this difference for each variable for 5% and 10% emission reduction standards, respectively.

S-4.3 Parameter correlations

We assume most model input parameters are independent. For the parameters shown in Table S-3, we assume partial correlation as shown. The column headings \( a \) through \( k \) refer to the parameters indicated by the same letter in the row headings. We used the Crystal Ball™ plug-in to Microsoft Excel™ to generate a set of trials in which the parameters observe the (rank) correlation structure below.
The modeled correlations are based on our subjective judgment, as follows.

- We assume that the demand elasticity for gasoline in the two regions is mildly correlated (0.5), and similarly for diesel and other petroleum products.

- We assume in either region, the demand elasticity for gasoline and diesel is more strongly correlated (0.7).

- We assume that CO$_2$ emissions for the three categories of petroleum products are strongly correlated (0.8) owing to the shared emissions from production, transport to the refinery, and for some refinery operations.

- Finally, we assume that ILUC emissions for corn and sugarcane ethanol are somewhat correlated (0.6) given that they both compete for land, and because models of ILUC emissions have many shared parameters used to calculate both quantities.

It is arguable whether these are the right values, but we’re confident that in the above cases, neither assuming zero correlation nor perfect correlation would be a better estimate than the intermediate values chosen. We examine the sensitivity of our results to the assumed correlations by comparing key model outputs for simulations assuming fully independent parameters, as described in §S-4.4.2.

Table S-3: Parameter correlation structure. Blank cells indicate zero correlation. Only the upper triangle is used.

| a. Gasoline demand elast., home | 1.0 | b. Gasoline demand elast., ROW | 1.0 | c. Diesel demand elast., home | 1.0 | d. Diesel demand elast., ROW | 1.0 | e. Other pet. demand elast., home | 1.0 | f. Other pet. demand elast., ROW | 1.0 | g. Gasoline CO$_2$e emissions | 1.0 | 0.8 | h. Diesel CO$_2$e emissions | 1.0 | 0.8 | i. Other pet. CO$_2$e emission | 1.0 | j. Corn ethanol ILUC emissions | 1.0 | 0.6 | k. Cane ethanol ILUC emissions | 1.0 |
Figure S-2: Comparison of model output parameters for a single trial using mean values for all parameters.
Figure S-3: Histogram of difference between outcomes under ES-ILUC and ES-NoILUC for a given stringency level for four variables, namely, global GHG emissions, global oil consumption, home oil consumption and the home price of blended gasoline. For each variable, $X$, denoted along the x-axis the histogram shows $X_{ES-ILUC} - X_{ES-NoILUC}$. The left panel is at the 5% stringency level and right panel is at the 10% stringency level of the emission intensity standard.
Figure S-4: Convergence of the first three moments (mean, standard deviation, and skewness) of net change in global CO$_2$-equivalent GHG emissions (left column) and the reduction in oil consumption in the home region (right column), for policies (a) SM-15 and (b) ES-ILUC-10, as functions of the number of trials. Tg = 10$^6$ metric tonnes, GL = 10$^9$ liters.
S-4.4 Sensitivity analysis

We examine model sensitivity to uncertainty in parameter values by computing the contribution of each parameter to the variance in select output parameters (§S-4.4.1) and to assumed correlations among certain parameters by running a simulation with uncorrelated parameters (§S-4.4.2).

S-4.4.1 Contribution to variance

We estimate contribution to variance using normalized rank (Spearman) correlations. For each input parameter, we compute the rank correlation with various output parameters across all trials. The rank correlations are squared and normalized to a percentage by dividing each by the sum of the squared correlation values. We restore the original sign to indicate directionality. Figures S-5 through S-12 show the percentage contribution to variance of the top ten most influential input parameters to (a) consumption of oil in the home region and (b) total global fuel CO$_2$e emissions.

- For policies SM-10 and SM-20, the top contributors to variance in home region oil reduction are gasoline demand in ROW and the supply elasticities for both corn and sugarcane ethanol. The order varies slightly between SM-10 and SM-20, but the percent contributions of these three are fairly similar. For both stringency levels, the ILUC GWI of corn and sugarcane ethanol each account for about 40% of the variance in the change in CO$_2$e emissions, followed by oil supply elasticity in ROW, which contributes about 5% of the variance.

- For the ES policies, sugarcane ethanol supply elasticity contributes 80–90% of the variance in home oil reduction in all cases. Corn ethanol supply elasticity make a non-trivial contribution only in the ES-NoILUC-5 case; in all other policies, no additional corn ethanol is used. Similarly, sugarcane ethanol ILUC emissions GWI is the top contributor to variance in the change in global CO2e emission, followed by sugarcane ethanol supply elasticity in all cases other than ES-NoILUC-5, in which the ILUC GWI and supply elasticity of corn ethanol rises to the second and third positions.

- For CT-10 and CT-20, demand elasticity for gasoline and diesel, in both regions are the top contributors to variance in home oil reduction, with gasoline having more influence than diesel, and the home region having more influence than ROW. In terms of the change in global CO$_2$e emissions, oil supply elasticity and corn ethanol ILUC emissions are the two top contributors in at both stringency levels, though the order is reversed, with corn ethanol ILUC emissions being more influential in the CT-10 case and less so in the CT-20 case. Sugarcane ILUC emissions is the third most important contributor at both stringency levels.
Uncertainty in the direct life cycle emissions for fossil and biofuels has a relatively small effect on overall variance in GHG emissions. Refined petroleum product GWIs are important under the carbon tax, and sugarcane direct GWI accounts for up to 10% of the variance in the change in global GHG emissions under the ES policies. Corn ethanol direct GWI is a non-negligible contributor only in the ES-NoILUC-10 scenario, contributing 12% of the variance.

![Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO\(_2\)e emissions, for policy SM-10.](image)

Figure S-5: Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO\(_2\)e emissions, for policy SM-10.
Figure S-6: Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO$_2$e emissions, for policy SM-15.
Figure S-7: Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO$_2$e emissions, for policy **ES-NoILUC-5**.
Figure S-8: Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO$_2$e emissions, for policy ES-NoILUC-10.
Figure S-9: Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO$_2$e emissions, for policy ES-ILUC-5.
Figure S-10: Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO$_2$e emissions, for policy **ES-ILUC-10**.
Figure S-11: Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO$_2$e emissions, for policy **CT-10**.
Figure S-12: Normalized rank correlations between each of the 10 most influential input parameters and (a) home oil reduction and (b) global change in CO$_2$e emissions, for policy CT-20.
S-4.4.2 Results with uncorrelated input parameters

To examine the effect of our assumed correlations between select parameters, we ran a separate 5000-trial Monte Carlo simulation with fully independent parameters. The results are qualitatively very similar but the distributions are somewhat wider in the uncorrelated case. Figures S-13 and S-14 show comparisons of output distributions for correlated and uncorrelated parameters for the reduction of oil consumption in the home region and the net global change in CO\textsubscript{2}e emissions.\textsuperscript{e1} Redo these figures with identical x-axes when we’re ready to submit.

Figure S-13: Box plots illustrating output distributions for the reduction in oil consumption in the home region, for correlated (top) and uncorrelated (bottom) input parameters. The green boxes represent the interquartile range; the vertical lines bisecting the green box shows the median. The vertical lines crossing the whiskers indicate the 95% confidence interval, and the ends of the whiskers indicate the minimum and maximum values.

(a) With correlated input parameters, as described in S-3.

(b) With uncorrelated input parameters.
Figure S-14: Box plots illustrating output distributions for net change in global CO$_2$e emissions, for correlated (top) and uncorrelated (bottom) input parameters.
References

