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

Antonio M. Bento[†], Richard Klotz[‡] and Joel R. Landry[††]

Charles H. Dyson School of Applied Economics and Management
Cornell University

[†] Associate Professor; amb396@cornell.edu
[‡] PhD Student; rlk99@cornell.edu
[††] PhD Student; jrl256@cornell.edu

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Abstract

This paper applies the insights of the carbon leakage literature to study the emissions consequences of biofuel policies. We develop a simple analytic framework to decompose the intended emissions impacts of biofuel policy from four sources of carbon leakage: domestic fuel markets, domestic land markets, world land markets and world crude oil markets. A numerical simulation model illustrates the magnitude of each source of leakage for combinations of two current US biofuel policies: the Volumetric Ethanol Excise Tax Credit (VEETC) and the Renewable Fuel Standard (RFS). In the presence of both land and fuel market leakage, current US biofuel policies are unlikely to reduce greenhouse gases. Four of the five policy scenarios we consider lead to increases in greenhouse gas emissions. That is, total leakage was greater than 100%. The single scenario that generates emissions savings, the removal of the VEETC in conjunction with a binding RFS, only does so because negative leakage in the domestic fuel market offset the remaining positive sources of leakage.

JEL Codes: Q42; Q54; Q58
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1 Introduction

Global climate change has enormous implications for many nations, with costs of mitigation alone expected to comprise 0.3 to 0.7% of global GDP by 2100 (World Bank [1]). [1] In the absence of effective global policy-making, many countries have initiated unilateral initiatives to reduce greenhouse gas (GHG) emissions. Given that the combustion of fossil fuels for transportation is a major source of greenhouse gas emissions—with passenger vehicles accounting for 22% of fossil fuel related emissions in the US alone—many countries, including the US, have implemented policies that attempt to expand the use of liquid biofuels, a substitute for fossil fuel based transportation fuels (US EPA [2]). Given that biofuel feedstocks absorb CO_2 during growth, biofuels are believed to provide emissions savings relative to fossil fuels (US EPA [3]). Policies that attempt to expand biofuels in order to exploit these potential emissions savings are expected to generate a meaningful reduction in total GHG emissions. However, the extent to which these policies will lead to emissions reductions ultimately depends upon complicated interactions that are typically not considered in the policy-makers original decision making process. With regard to greenhouse gas emissions, the emissions consequences of such interactions have been labelled “carbon leakage.”

Carbon leakage occurs when regulations affecting GHG emissions directly increase (or decrease in the case of negative leakage) emissions from unregulated firms, sectors or countries. In the presence of positive leakage, realized reductions in global emissions are smaller than the intended, or anticipated, emissions reductions. Early studies on carbon leakage related to energy markets measured increased GHG emissions in unregulated countries in response to unilateral or sub-global (e.g. the Kyoto Protocol) climate programs. Emissions were shown to increase in unregulated countries as a result of both producer relocation from regulated to unregulated regions (Babiker [4]) as well as from an increase in energy consumption in unregulated regions

[1] These estimates reflect the range across six peer-reviewed assessment models (DICE, FAIR, MESSAGE, MiniCAM, PAGE, and REMIND), and assume stabilization at 450 ppm CO_2e, which would provide a 40 to 50% chance of staying below 2 degrees warming by 2100 (World Bank [1]).

due to depressed world energy prices (Felder and Rutherford [5]). Recent work has demonstrated leakage due to incomplete regulation of a single sector (Fowlie [6]) and overlapping state and federal policies (Goulder et al. [7]). Another group of studies have shown that leakage may occur in land markets when policies, such as conservation or set-aside programs alter the relative returns to land faced by private landowners (Stavins and Jaffe [8], Murray et al. [9]).[2] Biofuel policies may alter both the prices of blended fuel and agricultural crops, and thus are subject to leakage in both energy and land markets. Prior analyses of the emissions from biofuel policies have failed to measure both sources of leakage in a comprehensive and coherent way.

The GHG emissions impacts of biofuels have mainly been studied using lifecycle analysis methods, which largely ignore economic adjustments (Farrell et al. [10]; Hill et al. [11]). Lifecycle analysis attempts to measure the total emissions attributable to a single unit of a biofuel, including emissions from inputs used in production, transportation, and final end use of the biofuel. If the lifecycle emissions of a unit of biofuel are less than the lifecycle emissions of an energy equivalent unit of the fossil alternative (gasoline or diesel), then that biofuel is said to achieve emissions savings. In the case of corn based ethanol, studies using these attributional lifecycle analysis methods have found GHG emissions savings on the order of 20% to 30% relative to gasoline (Farrell et al. [10]; Wang [12]). Using lifecycle emissions metrics, the US EPA's first regulatory impact analysis of the Renewable Fuel Standard (RFS), a series of gradually expanding biofuels mandates, estimated that the expanded use of 7.56 billion liters of corn ethanol in the US would reduce greenhouse gas emissions by 11 tgCO_2e (US EPA [13]).

More recent analyses have shown that the emissions generated by the clearing of undisturbed lands resulting from expanded corn ethanol production could be large enough to undermine any lifecycle emissions savings (Fargione et al. [14])[3] In light of these and other studies, the EPA updated the RFS to classify biofuels according to the *lifecycle emissions thresholds* that are inclusive of emissions attributable to land use change (US EPA [3]). The intention of these lifecycle emissions thresholds is to ensure that the RFS in fact reduces greenhouse gas emissions. The second regulatory impact analysis of the RFS conducted by the US EPA [16]—by far the most comprehensive emissions assessment of biofuels to date, incorporating agricultural models to assess domestic and international leakage from land use change and shifts in agricultural production—determined that corn ethanol just meets the 20% lifecycle emissions savings threshold put forth by legislators in establishing the RFS.

All prior assessments of the greenhouse gas impacts of biofuel policy have at least three key shortcomings. First, prior studies have not directly assessed the impact of specific US biofuel policy instruments on GHG

[2]Stavins and Jaffe [8] analyze the impacts of land conservation programs on wetland depletion rather than greenhouse gas emissions. However, the concept of leakage can be applied to both settings.

[3]Searchinger et al. [15] using an agricultural model to study the carbon leakage in land markets due to US biofuel policy, obtain a similar conclusion.

emissions. Instead, prior studies have relied either on lifecycle emissions savings metrics that do not account for potential economic adjustments, or have considered the impacts of an expansion in US biofuel consumption on emissions from land use with no reference to the policy driving the expansion (Searchinger et al. [15]; US EPA [16]).[4] Second, prior studies mostly ignore the emissions impact of expanded biofuel consumption on fuel markets.[5] This omission is especially problematic given that most biofuel policies directly impact fuel markets. Third, prior studies have not addressed how emission impacts vary with different magnitudes of biofuel expansion.

This paper attempts to address these shortcomings. First, we propose a very simple analytical model and derive a marginal emissions formula that decomposes the emissions consequences of a generic biofuel policy into intended emissions reductions and carbon leakage. Carbon leakage is further decomposed into domestic and international land and fuel market effects. Secondly, we provide empirical estimates of leakage resulting from a pair of US biofuel policies, the Volumetric Ethanol Excise Tax Credit (VEETC) and the Renewable Fuel Standard for corn ethanol, using a numerical general equilibrium model that is fully integrated with a comprehensive emissions accounting. This allows us to illustrate which economic adjustments drive the various components of carbon leakage resulting from biofuel policies from the perspective of the US regulator.

Our modeling framework integrates domestic agricultural and fuel markets and considers trade in agricultural crops and crude oil. To account for land market leakage, we model the agricultural land allocation decision, which allows for cropland expansion, and the demand for agricultural crops by domestic food and biofuel producers, as well as from abroad. From this framework, we are able to measure land market leakages from extensive (cropland expansion) and intensive (shifts to more emissions intensive crops) adjustments in domestic agriculture, and from international land use change. To capture energy market leakage we model the fuel blender's decision, which depends on he relative prices of gasoline and biofuel, while allowing for the prices of crude oil and agricultural crops to be determined endogenously. These features allow us to determine the impact of a policy on the domestic blended fuel price and the world price of crude oil. We will subsequently be able to assess the leakage in both of these markets.

Using our numerical model we simulate the emissions impacts of two US corn ethanol policies: the Volumetric Ethanol Excise Tax Credit (VEETC) and the Renewable Fuel Standard (RFS) for corn ethanol. The VEETC is a subsidy paid to the fuel blender for each unit of ethanol used to produce blended fuel.

[4] These studies analyze *any* expansion of biofuels, ignoring whether this expansion is induced by public policy or by market forces. However, most current discussions regarding appropriate reference baselines in global climate change negotiations are generally reflective of pre-existing and historical economic conditions.

[5] There are a handful of studies on the impact of biofuel policies on fuel markets (see for example deGorter and Just [17]), however these studies do not directly consider GHG emissions. Two exceptions are Rajagopal et al. [18] and Drabik et al. [19]. However, these studies do not consider agricultural or land use emissions. Moreover, none of these studies estimate emissions impacts across a theoretically consistent equilibrium model where prices of fuels and crops are jointly endogenously determined, as is the case here.

The RFS requires that fuel blenders include a minimum quantity of ethanol in each unit of blended fuel produced. The federal government sets the ethanol blend requirement annually, such that total US ethanol consumption is above a mandated level. Our results support prior studies that find considerable land market leakage from biofuel policies, however we find that in the presence of the VEETC, leakage in fuel markets can be of a similar magnitude. Further, while land market leakage tends to be stable across scenarios, leakage in fuel markets is substantially more variable and can be actually be negative if the VEETC is removed.

The rest of this paper is organized as follows. Section 2 develops an analytical model that describes the intended emissions effects and leakage from a marginal change in a generic biofuel policy. Section 3 outlines the functional form assumptions of our numerical model and describes the data used for calibration. Section 4 presents results, and Section 5 concludes.

2 Analytical Model

We first develop a simple analytical model that integrates the behavior of key agents affected by biofuel policies with greenhouse gas emissions. Using this framework, we derive a marginal emissions formula which decomposes the intended emissions impacts and carbon leakage that result from a generic biofuel policy. Carbon leakage is further broken down into four sources: domestic land markets, domestic fuel markets, world land markets and world crude oil markets.

2.1 Model Assumptions

We consider a model with two countries, D and W, with small open economies. We focus on country D, and let W be a collection of countries representing the rest of the world. Both countries, indexed k, are endowed with land ($\bar{A}_k$), labor ($\bar{L}_k$) and crude oil ($\bar{R}_k$). The countries trade agricultural crops and crude oil. All other goods, including the land and labor endowments, are assumed to be immobile. Therefore, the prices of crops and crude oil are determined on the world market, while all other prices are determined in domestic markets. Country D implements a new biofuel policy, Ω. The response of country W to Ω is determined only by changes in world prices. To simplify notation, in what follows we drop the index k for all country specific prices and goods.

We consider a representative consumer in each country, who enjoys utility from blended fuel (F), food (X) and a numeraire consumption good (C).[6] The household's utility function is represented by:

$$U(F, X, C) \tag{2.1}$$

where $U(\cdot)$ is continuous and quasi-concave. The budget constraint of the representative household is given

[6]For succinctness, we abstract from the choice of vehicle miles traveled (Parry and Small [20]) here.

by:

$$P_F F + P_X X + P_L C \leq \pi_{\bar{A}} + P_R \bar{R} + P_L \bar{L} \tag{2.2}$$

where P_F is the domestic price of blended fuel, P_X is the domestic price of food, P_L is the domestic wage rate[7], and $\pi_{\bar{A}}$ is the net returns to the country's land endowment.

The household chooses F, X, and C to maximize utility (2.1) subject to the budget constraint (2.2). From the resulting first-order conditions we obtain the Walrasian demand functions for blended fuel, food and the numeraire good:

$$F(P_F, P_X, P_L, \pi_{\bar{A}}, P_R) \qquad X(P_F, P_X, P_L, \pi_{\bar{A}}, P_R) \qquad C(P_F, P_X, P_L, \pi_{\bar{A}}, P_R). \tag{2.3}$$

Agricultural Production

Each country maximizes the net returns to its land endowment by allocating land to the production of a food-fuel crop, Y, a food crop, Z, or to non-agricultural uses, N. The food-fuel crop can be used as a feedstock for biofuel production, or to produce food, while the food crop represents all other crops. Non-agricultural land is all land of a quality sufficient for agricultural production but which currently sustains an alternative land use.[8] This framework allows the agricultural sector to adjust along both an intensive margin (changes within cropland) as well as an extensive margin (cropland expansion). Allowing the subscript i to index the three land uses, $\{Y, Z, N\}$, the land allocation problem is given by:

$$\max_{A_i} \sum_i \left(P_i y_i(A_i) - P_L c_i\right) A_i$$

subject to:

$$\sum_i A_i \leq \bar{A} \tag{2.4}$$

where P_Y and P_Z are world crop prices, A_i is the quantity of land allocated to land use i and c_i is the amount of labor required per unit land to produce crop i. The functions $y_Y(A_Y)$ and $y_Z(A_Z)$ are the yields (units of crop per unit land) of the food-fuel and food crops, respectively. Setting $P_N = 1$, the function $y_N(A_N)$ is the stream of monetary benefits to the land owner from holding land in non-agricultural uses.[9] To reflect decreasing returns to expanded agricultural production and decreasing marginal benefits from holding land

[7] C is assumed to be produced by competitive firms with the production technology $C = L$, so that in competitive equilibrium $P_C = P_L$.

[8] Alternative land uses could be forest, pasture, or land allocated to agricultural set aside programs.

[9] y_N may include the private returns to non-cropland land uses arising from long-run management practices, the revenue from the sale of products such as timber, and lower future costs of production from holding land fallow. Alternatively, y_N could reflect government payments to the land-owner for keeping land in non-agricultural uses. In this case, the revenue needed to finance such a program is funded from a head tax on the representative consumer.

in non-agricultural uses, $y_i(A_i)$ are assumed to be monotonically decreasing and concave.

The first order conditions of (2.4) provide the land supply functions:

$$A_Y(P_Y, P_Z, P_L, \bar{A}) \qquad A_Z(P_Y, P_Z, P_L, \bar{A}) \qquad A_N(P_Y, P_Z, P_L, \bar{A}) \tag{2.5}$$

which are used to generate the crop supply functions:

$$Y(P_Y, P_Z, P_L, \bar{A}) = y_Y\left(A_Y(\cdot)\right) A_Y(\cdot) \qquad Z(P_Y, P_Z, P_L, \bar{A}) = y_Z\left(A_Z(\cdot)\right) A_Z(\cdot). \tag{2.6}$$

Finally, we note that the value function of (2.4) is given by $\pi_{\bar{A}}(P_Y, P_Z, P_L, \bar{A})$.

Fuel Production

Blended fuel is produced from gasoline (G) and biofuel (E) by a representative *fuel blender* whose constant returns to scale production function is given by:

$$F = F(G, E). \tag{2.7}$$

The fuel blender chooses E and G to minimize production costs, $GP_G + EP_E$, subject to Equation (2.7), where P_E and P_G, are the domestic prices of biofuel and gasoline, respectively.[10] Under constant returns, the market price of blended fuel just equals the marginal cost of producing blended fuel, $P_F(P_G, P_E)$. Moreover, market closure implies that the demand for gasoline and biofuel are determined by the Walrasian demand for blended fuel, hence:

$$G = g_F(P_G, P_E)F(\cdot) \qquad E = e_F(P_G, P_E)F(\cdot) \tag{2.8}$$

where $g_F(\cdot)$ and $e_F(\cdot)$ are the per-unit conditional factor demands for gasoline and biofuel, respectively.

Gasoline and biofuel are produced by competitive firms under constant returns to scale with production technology denoted G and E respectively. Gasoline is produced from crude oil, R, while biofuel is produced from the food-fuel crop. The gasoline and biofuel production technologies are given by:

$$\begin{aligned} G &= G(R) \\ E &= E(Y_E) \end{aligned} \tag{2.9}$$

where Y_E is the food-fuel crop used for biofuel production. The gasoline producer chooses R to minimize

[10] The assumptions that gasoline and biofuel are not traded is generally representative of the US. Between 2005 and 2009, the US imported less than 3% of total finished gasoline consumed, and exported less than 5% of total gasoline produced (EIA). Over this same time, less than 7% of total ethanol consumed was imported (Renewable Fuels Association).

gasoline production costs subject to the gasoline production technology, taking the world price of crude oil as given. Equivalently, the biofuel producer chooses Y_E to minimize biofuel production costs, subject to the biofuel production function. The competitive domestic prices of gasoline and ethanol are the derivatives of the corresponding total cost function with respect to output and can be written $P_G(P_R)$ and $P_E(P_Y)$.

The fuel blender's decision is modeled explicitly for two reasons. First, this specification allows fuel to be treated as the final consumption good rather than gasoline and biofuel. This matches current fuel market characteristics in the US, because with only some minor exceptions, consumers are unable to choose the quantity of biofuel in the fuel they purchase.[11] Second, this permits us to handle a number of biofuel policies, and to trace out the impacts of these policies on the price of blended fuel. For example, Ω could consist of a subsidy for biofuel consumption or a quantity restriction on biofuel.

Food Production

Incorporating the food sector allows for an explicit trade-off between demand for agricultural products for food production, and demand for agricultural products for biofuel production. Food is produced from food-fuel crop and the food crop by competitive firms with constant returns to scale production technology:

$$X = X(Y_X, Z_X) \tag{2.10}$$

where Y_X is quantity of the food-fuel crop used in food production, and Z_X is the quantity of the food crop used for food production. The food producer chooses Y_X and Z_X to minimize production costs $P_Y Y_X + P_Z Z_X$ subject to the food production technology, taking the world prices of crops as given. The solution to this problem yields conditional factor demand equations that describe the quantities of the food-fuel crop and the food crop allocated to food production

$$Y_X(P_Y, P_Z, X) \qquad Z_X(P_Y, P_Z, X) \tag{2.11}$$

and a total cost function for food production. Differentiating the total cost function with respect to output yields the competitive price of food $P_X(P_Y, P_Z)$, which given constant returns is independent of output.

Equilibrium

Normalizing the domestic wage rate in country D, $P_{L,D} = 1$, an equilibrium consists of a price vector, $[P_Y, P_Z, P_R, P_{L,W}]$, such that the world markets for agricultural crops (Y and Z) and crude oil, and the

[11] In the US, consumers can choose among various biofuel gasoline blends. However, the vast majority of blended fuel sold contains 10% ethanol, called E10, because this fuel can be used in a standard gasoline vehicle (EIA). Higher percentage blends, such as E85, require additional infrastructure to distribute, and a special flexible-fuel vehicle to consume. These restrictions have limited the market penetration of higher ethanol blends.

labor markets in countries D and W clear.[12]

Emissions

Greenhouse gas emissions are modeled using constant marginal emissions factors that specify the amount of greenhouse gas emissions, in units of carbon dioxide equivalent, per unit of a given product or activity. To facilitate the exposition of the greenhouse gas emissions impacts below, we assume that country W does not produce biofuel. Further, we abstract from the emissions from crop production in country W.[13] Therefore, variables below that are not indexed by country are for country D.

The total contribution to greenhouse gas emissions of a unit of gasoline, or the lifecycle emissions of gasoline, are $\phi_G = \phi_{G,C} + \phi_{G,M}$. The emissions from gasoline consumption (combustion) are $\phi_{G,C}$, which effectively maps the chemical characteristics of gasoline to greenhouse gas emissions (NETL [21]). The production of gasoline generates emissions at a rate of $\phi_{G,M}$ per unit output. This factor accounts for the fossil fuels combusted during crude oil refining and crude oil recovery (NETL [21]).

Following the IPCC [22], we assume that the consumption (combustion) of biofuel has no impact on atmospheric greenhouse gas concentrations, $\phi_{E,C} = 0$. This reflects that the carbon stored in biofuel, and released during biofuel combustion, is absorbed from the atmosphere during the growth of the biofuel feedstock. The manufacture of biofuel generates emissions at a rate of $\phi_{E,M}$ per unit biofuel, due to fossil fuels used in the production of the biofuel. This illustrates an important point. Holding all else equal, increasing the quantity of biofuel in the economy will increase total emissions because the production of biofuel generates emissions. It follows that biofuel policies can only achieve emissions savings to the extent that the consumption of gasoline is displaced by the consumption of biofuel.

As we abstract from biofuel consumption in country W, we can calculate total fuel emissions in the rest of the world based on the consumption of crude oil. We assume that the consumption of crude oil in country W produces emissions at a rate of ϕ_R per unit crude oil.

Each unit of land allocated to the production crop Y and Z produces ϕ_Y and ϕ_Z units of greenhouse gas emissions respectively. These factors capture emissions from interactions between agricultural soils and farm inputs (such as nitrogenous fertilizer and lime) and on-farm fossil fuel combustion, as well as emissions from the production of farm inputs. In contrast, non-agricultural land uses provide emissions benefits through the uptake of atmospheric carbon by undisturbed land cover (such as the growth of forest or grasslands) and through increased carbon sequestration in soils (Fargione et al. [14]). These benefits are lost when non-

[12] By market clearing, it is the case that the total endowment of crude oil is consumed regardless of biofuel policy. This illustrates an extreme example in which any reductions in US crude oil consumption are completely offset by increased world consumption. This is a result of our inability to capture the dynamic components of the crude oil production decision, based on expectations of future prices, in our static framework.

[13] As noted by the EPA [16], adjustments in world crop mix resulting from US biofuel policy could be a source of leakage. However, the magnitude of this leakage is likely to be small in comparison to emissions from expansions in world cropland, and these adjustments fall outside the scope of our numerical model.

agricultural land is brought into agricultural production. We specify $\phi_{N,k}$ to represent the annual emissions benefits of holding land in non-agricultural uses, so that a reduction in land allocated to non-agricultural uses results in positive emissions. We emphasize that $\phi_{N,k}$ differs across the two countries to reflect that the climate benefits provided non-agricultural land uses are largely driven by regional characteristics (US EPA [16], Fargione et al. [14], Searchinger et al. [15]).

Given our modeling framework, total emissions, Φ, are given by:

$$\Phi = \phi_G G + \phi_{E,M} E + \phi_Y A_Y + \phi_X A_X + \phi_{N,D} A_{N,D} + \phi_{N,W} A_{N,W} + \phi_R R_W. \tag{2.12}$$

where all quantities and emissions factors are specific to country D unless otherwise indexed.

2.2 Marginal Emissions Effects

The impact on greenhouse gas emissions of a marginal increase in a generic domestic biofuel policy, Ω, given 2.12, is:[14]

$$\frac{d\Phi}{d\Omega} = \overbrace{\left(\phi_{E,M} + \phi_Y \tilde{A}_Y - \phi_G\right)\frac{dE}{d\Omega}}^{\text{Intended Effect}}$$
$$\overbrace{\underbrace{+\phi_G \frac{dF}{d\Omega}}_{\text{Domestic Fuel}} \underbrace{+\phi_Y\left(\frac{dA_Y}{d\Omega} - \tilde{A}_Y\frac{dE}{d\Omega}\right) + \phi_Z\frac{dA_Z}{d\Omega} + \phi_{N,D}\frac{dA_{N,D}}{d\Omega}}_{\text{Domestic Land}} + \underbrace{\phi_{N,W}\frac{dA_{N,W}}{d\Omega}}_{\text{World Land}} + \underbrace{\phi_R\frac{dR_W}{d\Omega}}_{\text{World Crude}}}^{\text{Leakage}}. \tag{2.13}$$

The first term on the right-hand side of Equation (2.13) consists of the intended emissions effects of this policy. The intended emissions savings of the policy are the expected emissions reductions of the policy calculated using lifecycle analysis (LCA) techniques.[15] This effect equals the per unit lifecycle emissions savings of biofuel relative to gasoline multiplied by the change in biofuel consumption due to the policy. Three main assumptions are implicit in the lifecycle emissions savings of biofuel (see for example Farrell et al. [10] or US EPA [13]). First, the production of a unit of biofuel generates emissions of $\phi_{E,M}$. Second, $\lambda_{E,Y}$ units of the food-fuel crop are need to produce each unit of biofuel, and an additional $\tilde{A}_Y = \frac{\lambda_{E,Y}}{y_Y(\cdot)}$ units of land are allocated to food-fuel crop production per unit of biofuel. Explicitly, $\tilde{A}_Y$ is the amount of land, in units of area, required to produce one unit of biofuel. Finally, each energy unit of biofuel displaces one energy unit of gasoline. A consequence of this last assumption is that the intended emissions impacts are

[14]See Appendix A.1 for derivation.

[15]Our construction of the intended emissions effects was necessary because biofuel policies do not target a level of emissions reductions. Lifecycle methods were used because this is a technique commonly used by regulators. For example, the US EPA's initial Regulatory Impact Analysis of the Renewable Fuel Standard assigned emissions savings to each energy unit of corn ethanol according its lifecycle emissions savings relative to an energy equivalent unit of gasoline [13]. More recently, the EPA has required each class of biofuels to achieve a given lifecycle emissions thresholds [3].

linear in the quantity of biofuel added by the policy ($\frac{dE}{d\Omega}$).

The remaining terms on the right-hand side of equation (2.13) denote the unintended emissions effects of the biofuel policy. The first unintended effect is leakage in domestic fuel markets (Domestic Fuel). This effect equals the lifecycle emissions of gasoline multiplied by the change in blended fuel consumption due to biofuel policy. We refer to $\frac{dF}{d\Omega}$ as the “output effect”, which occurs if biofuel policy has an impact on the price, and therefore the consumption, of blended fuel.

The next group of terms (Domestic Land) is leakage in domestic land markets. This effect is the emissions from unintended changes in domestic land use due to the policy. Domestic land market leakage consists of three components.[16] The first component is leakage from the domestic production of the food-fuel crop. This component is equal to the change in emissions from the production of the food-fuel crop less the projected change in emissions from the production of the food-fuel crop calculated with LCA methods. The second component of domestic land market leakage is the change in emissions from food crop production. This effect is the product of the lifecycle emissions of food crop production and the change in the amount of land allocated to food crop production due to the policy. The final component of domestic land market leakage are the emissions from policy induced domestic land use change. This component is equal to the lifecycle emissions benefits of non-agricultural land uses, multiplied by the change in the quantity of land allocated to non-agricultural uses.

The final two terms (World Land and World Crude) on the right-hand side of Equation (2.13), represent leakage in world markets. Leakage in world land markets is equal to the emissions benefits of rest-of-world land held in non-agricultural uses, multiplied by the change in world land allocated to non-agricultural uses. Leakage in world crude oil markets equals the lifecycle emissions from crude oil consumption multiplied by the change in world crude oil consumption due to the biofuel policy.

Expected Emissions Effects

The intended impact on emissions of any policy that increases biofuel consumption will be negative if the lifecycle emissions of ethanol are less than the lifecycle emissions of gasoline ($\phi_G > \phi_{E,M} + \phi_Y \tilde{A}_Y$). This is an appropriate assumption for most biofuels (Farrell et al. [10], Hill et al. [11]). However, in the presence of leakage, the net impact of a biofuel policy on emissions is ambiguous. Further, each of the leakage terms are not necessarily positive. Positive leakage is the standard case, where unintended emissions offset the intended emissions of a policy. Negative leakage indicates that policy induced market adjustments generate emissions savings additional to the intended emissions saving.

Leakage in domestic fuel markets can be negative or positive. If the output effect is positive, that is

[16] We note that this analysis can be extended to consider multiple agricultural crops with different characteristics (yields, emissions factors) or multiple non-agricultural land uses with different climate benefits.

the consumption of blended fuel increased due to the policy, then leakage in domestic fuel markets is also positive. Negative leakage in domestic fuel markets occurs when the biofuel policy reduces the consumption of blended fuel.

The direction of leakage in domestic land markets is also unclear. We expect that LCA methods will over estimate the amount of additional land that would be allocated to the food-fuel crop due to the policy, that is $\frac{dA_Y}{d\Omega} < \tilde{A}_Y \frac{dE}{d\Omega}$. This is because the additional food-fuel crop required for expanded biofuel production can be diverted from other end uses, such as food production, or produced on additional land allocated to the food-fuel crop. The LCA calculations do not consider these adjustments. In our framework, this overestimate represents a negative leakage from food-fuel crop production.

As biofuel policy induces additional land to be dedicated to the production of the food-fuel crop, the amount of land allocated to other agricultural crops and non-agricultural land uses decreases. The reduction in land allocated to other crops also results in negative leakage. However, to the extent that non-agricultural land uses provide greenhouse gas benefits, the reduction in land allocated to non-agricultural results in a positive leakage.

Leakage in world land markets and world crude oil markets are both expected to be positive. In the framework presented here, a biofuel policy would increase the domestic demand of the food-fuel crop, and cause the world prices of crops to increase. The land owner in country W would respond to the higher crop prices by allocating additional land to agriculture, which would generate a positive leakage. Any biofuel policy that reduces domestic gasoline consumption will reduce the domestic demand for crude oil. Subsequently, the world price of crude oil P_R will decline and the world consumption of crude oil will increase, resulting in positive leakage in world crude oil markets.

3 Numerical Model

We supplement the analytical model developed above with a numerical model where the United States is the domestic economy. Using this numerical model we are able to compute estimates of the terms of equation (2.13) for large-scale US corn ethanol policies over the years 2009-2015. Key differences between the analytical and numerical model include: an explicit model of vehicle-miles-traveled which allows us to incorporate endogenous adjustment in fuel economy which can amplify or suppress the output effect on blended fuel; closure of the domestic government by a head tax on the domestic representative agent; the introduction of labor in the production of ethanol, regular gasoline, and food in order to properly calibrate the sizes of the relative sectors; and allowing domestic and international income, yields, ethanol production technology, average fuel economy, and average crude oil prices to adjust exogenously between years in order to provide accurate predictions of the impacts of different biofuel policy instruments on the various sources of greenhouse gas emissions over time.

This section proceeds by first discussing the various US policies for corn ethanol that we evaluate. Second, we present the functional forms used in our numerical model. Third, we discuss the data sources used to identify and calibrate the model. Finally, we describe the emissions factors which translate the economic predictions of the model into greenhouse gas emissions.

3.1 Policy Instruments Considered

The policy scenarios we consider consist of different combinations of two current US biofuel policies for corn ethanol: the Volumetric Ethanol Excise Tax Credit (VEETC) and the Renewable Fuel Standard (RFS) for conventional biofuels.

The VEETC is a tax credit, or input subsidy, provided to the fuel blender for each unit of ethanol used in the production of blended fuel. The VEETC was created by the American Jobs Creation Act of 2004 and was set to its current level, \$0.12/liter (\$0.45/gallon), in the 2008 Farm Bill.[17] The VEETC is currently set to expire at the end of 2011. Although the VEETC and its forebears have been renewed repeatedly in the past, there is considerable uncertainty regarding whether it will be renewed in the future given the current legislative climate.[18] For the purposes of our analysis we assume that the VEETC is maintained at its current level through 2015.

The RFS is a set of nested quantity mandates for biofuels specified by the Energy Independence and Security Act (EISA) of 2007, with rule-making authority provided to the US EPA. We focus on the RFS for corn ethanol (conventional biofuels), which expands monotonically from 15.1 billion liters (4 billion gallons) in 2006 to 56.7 billion liters (15 billion gallons) in 2015. While the RFS itself states the total amount of ethanol that must be used, in practice the EPA annually determines the minimum share of ethanol that must be mixed into each liter of blended fuel. The blend requirement is set such that, given projected demand for blended fuel, the resulting total consumption of ethanol in a given year approximately equals the RFS [3,13]. Given that the RFS is implemented as a share mandate on ethanol, it follows that, when binding, the RFS also imposes a share quota (or ceiling) on gasoline used in each liter of blended fuel.

3.2 Functional Forms

In what follows we specify functional forms for key sectors of our numerical model. We begin by outlining those for the US (domestic) economy. The domestic model is slightly more sophisticated than that considered in Section 2, but all of the important dimensions of adjustment remain undisturbed. Finally, we specify the functional forms used to model the rest-of-world economy. We focus on world leakage from cropland

[17] Ethanol production has been subsidized in the form of an excise tax exemption since the 1978 Energy Tax Act.

[18] The VEETC was scheduled to expire in December of 2010, but was extended through December of 2011 as part of 2010 tax compromise [23].

expansion and crude oil consumption, which are fully determined through two key channels, crude oil prices and crop prices. Thus, we model these two channels explicitly, which is sufficient for our purposes. We note, however, that a more explicit treatment of world land use, including adjustments in cropland allocation, could improve this analysis.

Consumer

The representative agent in the US[19] is assumed to have preferences given by the following nested constant elasticity of substitution (CES) utility function:

$$\begin{aligned} U(F,X,C,H) &= \left[\alpha_{U1,M} M^{\frac{\sigma_{U1}-1}{\sigma_{U1}}} + (1-\alpha_{U1,M})\, U2A(C,X)^{\frac{\sigma_{U1}-1}{\sigma_{U1}}}\right]^{\frac{\sigma_{U1}}{\sigma_{U1}-1}} \\ U2A(C,X) &= \gamma_{U2a}\left[\alpha_{U2a,C} D^{\frac{\sigma_{U2a}-1}{\sigma_{U2a}}} + (1-\alpha_{U2a,C})\, D^{\frac{\sigma_{U2a}-1}{\sigma_{U2a}}}\right]^{\frac{\sigma_{U2a}}{\sigma_{U2a}-1}} \\ M(F,H) &= \gamma_{U2b}\left[\alpha_{U2b,F} F^{\frac{\sigma_{U2b}-1}{\sigma_{U2b}}} + (1-\alpha_{U2b,F})\, H^{\frac{\sigma_{U2b}-1}{\sigma_{U2b}}}\right]^{\frac{\sigma_{U2b}}{\sigma_{U2b}-1}} \end{aligned} \qquad (3.1)$$

where σ_{U1}, σ_{U2a}, and σ_{U2b} are exogenous elasticities of substitution corresponding to each nest, $\{1, 2a, 2b\}$; $\alpha_{U1,M}, \alpha_{U2a,C}, \alpha_{U2b,F} \in (0,1)$ are exogenous share parameters; and γ_{U2a} and γ_{U2b} are exogenous scale parameters. Nesting utility in this way implies weak-separability between vehicle-miles-traveled[20] (VMT, M) and the demand pair (C, X). In embedding the VMT decision we permit substitutability between fixed costs of driving, H and blended fuel, F, allowing fuel economy to be endogenously determined. Both nests permit a more accurate characterization of demand response with respect to blended fuel.

Land Use Allocation

The land owner's decision follows closely equation (2.4), except that we allow the land owner to allocate land to five crops as well as a single non-agricultural land use. The agricultural crops we consider are corn, soybeans, hay, wheat, and cotton. These five crops together make up the majority of U.S. agriculture both in terms of area and economic value.[21]

The non-agricultural land use that we consider is land held in the Conservation Reserve Program (CRP), which is the most direct substitute for cropland. The CRP is a government funded program, administered by the USDA, which allows farmers to voluntarily take land out of agricultural production in exchanged for rental payments.[22] Given our earlier convention, we simply note for completeness that Y is corn, Z

[19] Here and in what follows, we again drop the subscript D on the parameters of these functions to simplify notation.

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

[21] For each year since 1980, these five crops have made up at least 80% of total principal crops harvested. This share has generally been increasing over time, and was 91% in 2003. In 2003, these five crops represent 82.7% of the total value of field crop production (NASS [24]).

[22] There are four major CRP programs, with varying contract lengths, payment rates and enrollment qualifications [25]. Two of these programs, the Conservation Reserve Enhancement Program (CREP) and the Farmable Wetland Program (FWP) target specific environmental objectives and offer higher rental rates making this land unlikely to be converted to cropland.

is soybeans, wheat, hay and cotton and N is land held in the CRP. In what follows we simply re-use our original i subscript to denote each of these six final land-uses. Thus all functions in equation (2.4) remain the same.

We assume a linear functional form for the yield (benefit) functions in equation (2.4):

$$y_i(A_i) = \beta_i - \delta_i A_i \tag{3.2}$$

where β_i is the endogenous intercept term for crop i's linear yield function and δ_i is the exogenous slope term for crop i's linear yield function.

To simplify matters, we assume that corn is the sole biofuel feedstock. Corn, soybeans, hay and wheat are all used in domestic food production. Corn, soybeans, wheat and cotton are exported.

Fuel Markets

Fuel blenders produce blended fuel, equation (2.7) in the analytical model, according to the following linear production function:

$$F = \Gamma_F E + G \tag{3.3}$$

where Γ_F reflects that we treat ethanol as if it is a per unit energy perfect substitute for gasoline.

The VEETC enters as a price wedge of magnitude s_E in the input price for ethanol. When the RFS is not binding or not present, the fuel blender's profit maximization problem implies:

$$\Gamma_F = \frac{P_E - s_E}{P_G} \tag{3.4}$$

In the absence of the RFS, or when the RFS is not binding, we can re-specify (3.3) as implying $E = \Theta_F F$ and $G = (1 - \Gamma_F \Theta_F)F$, where Θ_F is the endogenous share of ethanol in blended fuel. While no analytical solution for E and G is possible that satisfies (3.4), Θ_F can be identified numerically by searching over the subset of price equilibrium such that (3.4) is satisfied. In this case Θ_F is such that the per MJ price of the two fuels is exactly equal. We also note that an increase in the VEETC, implies an increase in Θ_F, e.g. $\frac{d\Theta_F}{ds_E} > 0$.

The RFS imposes the following additional constraint on fuel blenders in the US:

$$E \geq \theta_F F \tag{3.5}$$

We therefore assume that only land in the remaining two major programs, general sign-up and continuous non-CREP, will be available for conversion to cropland. Thus when we refer to 'CRP' land in this paper, we are referring only the sum of these two sub-categories.

where θ_F is the share mandate. We say that the RFS is binding when (3.5) binds, that is when $\theta_F > \Theta_F$, where the latter must be first identified numerically.

Profit maximization under perfect competition implies that the market price that consumers pay for blended fuel just equals the marginal cost of producing blended fuel. This has two solutions. When the RFS is either not binding or not present, we have:

$$P_F = (1 - \Gamma_F \Theta_F) P_G + \Theta_F (P_E - s_E) \tag{3.6}$$

and when the RFS is binding we have:

$$P_F = (1 - \Gamma_F \theta_F) P_G + \theta_F (P_E - s_E) . \tag{3.7}$$

It is now easy to see the condition when $dF > 0$ in (2.13). Allowing the superscripts θ and Θ to denote equilibrium prices under the RFS and in the absence of the RFS, respectively, we see that this occurs when $\theta_F(P_E^{\theta} - s_E) - \Theta_F(P_E^{\Theta} - s_E)$ is less than $(1 - \Gamma_F\theta_F)P_G^{\theta} - (1 - \Gamma_F\Theta_F)P_G^{\Theta}$. That is the price of blended fuel increases when the share weighted increase in the price of ethanol is less than the share weighted decrease in the price of gasoline. Likewise when $dF < 0$ the opposite is true.

Ethanol is produced according to the following Leontief production function:

$$\min\left\{\frac{L}{\lambda_{E,L}}, \frac{Y}{\lambda_{E,Y}}\right\} = E \tag{3.8}$$

where L is per liter of ethanol expenditures on labor, capital and energy, and Y is corn used in the production of ethanol, net of co-products.[23] Here $\lambda_{E,Y}$ and $\lambda_{E,L}$ are exogenous parameters that state how much of each input is required to produce each liter of ethanol.

Refiners produce regular gasoline so as to maximize profits by combining labor and crude oil according to the following nested CRTS CES technology:

$$P(R, L) = \gamma_P \left[\alpha_{P,R} R^{\frac{\sigma_P - 1}{\sigma_P}} + (1 - \alpha_{P,R}) L^{\frac{\sigma_P - 1}{\sigma_P}}\right]^{\frac{\sigma_P}{\sigma_P - 1}} \tag{3.9}$$

where $\alpha_{P,R} \in (0, 1)$ is an exogenous share parameter, γ_P, is an exogenous CES scale parameter, and σ_P is the elasticity of substitution. We assume for simplicity that the US does not domestically produce crude oil, but imports all crude oil it requires to produce gasoline.[24]

[23]We note that co-products include dried distillers grains, corn gluten meal, corn gluten feed, and corn oil, which are substitutes for corn and soybeans in food production. Given a coefficient of conversion for each of the co-products, we deduct, for simplicity, the corn equivalent values of co-products from $\lambda_{E,Y}$.

[24]This assumption is easily justified because we parameterize the rest-of-world crude oil supply to include US crude oil

Other Sectors

We assume that fixed costs of driving, per unit expenditures on land production (c_i), and the numeraire good are produced linearly from labor. Food is produced from corn, soybeans, wheat, ethanol co-products and labor. Equivalent[25] corn, equivalent soybeans, wheat, hay, and labor are modeled according to a nested CRTS CES function structured so as to permit the substitution patterns with respect to corn that are appropriate for our analysis (according to the following ranking: soybeans>wheat>hay). Finally, to close the behavior of the government we assume that the government raises revenue from a labor tax on the domestic representative agent, which after financing the VEETC and land held in CRP, is returned as a lump-sum transfer to the agent. We note, that since leisure does not enter the utility function, that this simplifies to a non-distorting uniform head tax on the representative agent.

World Crop Demand

To model rest-of-world consumption of agricultural products, we specify the following iso-elastic inverse excess (or import) demand functions:

$$P_i = \gamma_i \left(Q_i - \tau_i\right)^{\frac{1}{\eta_i}} \tag{3.10}$$

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

World Crude Oil Supply

In the current framework, we consider a highly stylized and simplistic model of crude oil supply, and that abstracts from market power considerations with respect to the production and refinement of crude oil. We specify the inverse rest-of-world excess (or export) supply of crude oil as:

$$P_R = \gamma_R \left(R - \tau_R\right)^{\frac{1}{\eta_R}} \tag{3.11}$$

where R is the amount of crude oil (net of demand) supplied by the rest of the world, γ_R is a scale parameter, τ_R is a shift parameter, and η_R is the rest-of-world supply elasticity for crude oil. We note that by specifying (3.11) as inverse excess supply (demand) functions, that we are implicitly specifying a combination of iso-elastic demand and supply functions for the rest of the world.

consumption.

[25]Co-products are simply deducted (as perfect substitutes) from the corn and soybeans otherwise demanded by the food sector.

3.3 Data and Calibration

Table A.1 presents the characteristics of the US economy for the calibration year, 2003. Table A.2 reports key calibration parameters for the general economy, while Tables A.3 and A.4 display calibration parameters for the domestic land use model. We chose the year 2003 to calibrate our model because it precedes several anomalous years, prior to our period of analysis, where crop (NASS [24]) and crude oil prices (EIA [26]) were well above historic levels. Also, our primary data source for agricultural input data, the USDA's Agricultural Resource Management Survey (ARMS), is conducted for each major crop on a rotating quadrennial basis and 2003 is the central year of a recent four year cycle.

Benchmark Economy

In 2003, US GDP was roughly $7.7 trillion, with the value of the labor and capital endowments accounting for $2.8 trillion and $3.5 trillion respectively (BEA [27]). Net government transfers to households make up $2,828.90 billion (BEA [27]). While not explicitly denoted in our analytical or numerical model, the government raises revenue on the representative agent by levying a tax on labor at the rate reported in Table A.1.

In 2003, 112.68 million hectares of cropland were allocated to the five crops considered. Corn was the dominant crop in terms of land area, with 31.37 million hectares, followed by soybeans, hay, wheat and cotton. In addition to cropland, 13.57 million hectares were held in the Conservation Reserve Program.[26] In 2003, the government funded CRP rental rate was 114.48 $/hectare.[27] Crop prices, reported in Table A.1, represent national average prices reported by the USDA (NASS [24]). US average yields for corn, soybeans, hay, wheat and cotton are 8.9, 2.6, 6.1, 3.0 and 0.8 metric tons per hectare respectively (NASS [24]). Given agricultural production costs (discussed below), the net returns from land holdings were $27.6 billion in 2003, which is small in comparison to total GDP.

Benchmark blended fuel consumption in 2003 was 499.97 billion liters, while total regular gasoline consumption was 490.28 billion liters.[28] Total ethanol consumption was 10.39 billion liters [29]. The 2003 price of regular gasoline, 0.23 $/liter, represents the consumption weighted US average spot price for all grades of conventional gasoline from [26]. We compute a spot price for ethanol in 2003 of 0.35 $/liter. This price consists of the marginal cost of ethanol production less the value of co-products sold to food producers, plus the average cost of transporting ethanol to end users. We note that this is very close to the average 2003

[26] 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 [25]. This intentionally excludes 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.

[27] This value was computed from the USDA Farm Service Agency reports [28] and represents the weighted average annual rental payment to land in the general sign-up and non-CREP continuous sign-up programs.

[28] Our value for total regular gasoline consumption is slightly higher than the volume reported by the FHWA [29].

spot price for deliveries to Omaha, Nebraska which was 0.36 $/liter [30].[29] Given benchmark quantities and prices of gasoline and ethanol, the 2003 price of blended fuel, inclusive of the fuel tax and pre-existing VEETC, was 0.41 $/liter.

Consumer

We specify an elasticity of substitution between miles and non-mile expenditures, σ_{U1}, of 0.50, between food and the numeraire good, σ_{U2a}, of 0.09, and between fuel and non-fuel expenditures on driving, σ_{U2b}, of 0.21. These imply a calibrated own-price elasticity of demand for miles of -0.53, an own-price elasticity of demand for food of -0.12, and an own-price elasticity of demand for blended fuel of -0.34.

Our calibrated own-price elasticity of demand for miles is intentionally more elastic than literature values for the (negative) of the elasticity of VMT with respect to the price of fuel. Summaries of this literature (see [31–33]) report means for short-run estimates between -0.10 and -0.26 and long-run estimates of -0.26 and -0.31. More recent estimates (Small and Vendender [34]) report short-run elasticities between -0.045 and -0.022. Given that we assume that fuel expenditures represent 40% of the total cost of driving, following Parry and Small [20], our short-run calibrated estimate of the elasticity of VMT with respect to the price of fuel is on the higher end of the literature at -0.21, but consistent with Parry and Small [20]. Our calibrated own-price elasticity of demand for blended fuel is on the high end of recent empirical estimates (Small and Van Dender [34] and US DOE [35]).

Estimates of the own-price elasticity of food demand are considerably more sparse. Our estimate is roughly consistent with the estimates of [36], who estimates the own price elasticity for a broad consumption group of “food, beverages and tobacco” in the range of -0.075 to -0.098.

Land Use Allocation

To construct the per unit land labor expenditures for agricultural production (c_i), we sum expenditures over four broad input categories: labor, capital energy and fertilizer (Table A.3). Expenditures on labor and capital are from the USDA’s Commodity, Costs and Returns (CCR) [37]. 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 more detailed input use data and subsequently use this data to calculate crop specific emissions factors (discussed below). Our estimates for energy expenditures are aggregates of expenditures on diesel, gasoline, natural gas, electricity and liquefied petroleum gas. Diesel

[29] The transportation cost term is necessary to reconcile the spatial concentration of historical spot price data for ethanol. Historic ethanol price data is limited. Most spot prices for ethanol are reported as the price of FOB (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 price of ethanol to reflect deliveries of ethanol across the country.

use for each crop was derived from West and Marland [38] and Nelson et al. [39]. Crop specific use of the other energy sources were derived from the lifecycle analysis literature (Farrell et al. [10], Hill et al. [11], Piringer and Steinberg [40]). 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 the USDA's ARMS dataset [41] and national prices from the USDA's ERS [42].[30] Second, expenditures on other variable inputs are from the CCR [37].[31] The fertilizer expenditure variable is disaggregated in the lower panel of Table A.3.

Land Supply Elasticities

The six δ_i in (3.2) determine the supply response of the US land market. We estimate the δ_i using a method that advances the 'full-solution' method used by Ferreyra [43].[32] Our estimation strategy exploits the implied land supply elasticities between multiple equilibrium solutions. This proceeds in a recursive manner whereby the previous equilibrium solution $(t-1)$ is exogenous to the current (t) identification of the parameter vector $\boldsymbol{\delta}^t$ and thus also the current equilibrium solution.[33] Given these two equilibrium solutions we compute the implied land supply elasticity, searching for the $\boldsymbol{\delta}^t$ that minimizes the Euclidean distance between this estimate and elasticities estimates taken from the literature. Literature estimates are reported in Table A.4 and are assumed fixed throughout.

We believe that this estimation strategy provides two main benefits. First, it ensures proper calculation of the counter-factual amount of ethanol that would be produced in the absence of various biofuels policies. Second, it allows for the proper calculation of the domestic emissions leakage related to land-use change. We refer the interested reader to Bento and Landry [45] for a detailed exposition of our estimation strategy, as well details on model validation given this approach.

Fuel Markets

The ratio of the energy content of ethanol to gasoline, $\Gamma_F = 0.67$, is based on low heating values from GREET 1.8c [12]. We note that our linear specification for the production of blended fuel is not identified

[30] 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.

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

[32] While most strategies for estimating the parameters of large-scale computable general equilibrium models involve two stages—a first stage whereby historical data is used to estimate a sub-portion of the model's parameters, or simply the parameter vector of interest, and a second stage where the parameter vector is fixed and the model itself is solved for an equilibrium (See Bento et al. [44] for a recent application). 'Full solution' methods estimate a parameter vector through an iterative process that computes a separate equilibrium solution for each attempted parameter vector.

[33] We identify the first parameter vector for $t = 0$, by considering a small exogenous increase in ethanol over the amount realized in the calibration year, which is the equilibrium that is presumed exogenous for identification. For $t > 0$, we estimate a baseline series of parameter vectors, treating the previous year's baseline as exogenous for identification. In addition, we also estimate a post-policy series of parameter vectors that treat the current year's baseline as exogenous for identification.

on the basis of an estimate of the elasticity of blended fuel. This is to our advantage, as the elasticity of blended fuel will be determined unencumbered by the underlying elasticities of gasoline and ethanol.

The per unit ethanol input requirements in equation (3.8), are calibrated to reflect an average ethanol production facility in the US. In 2003, we assume that the net of co-products corn to ethanol conversion ratio was 1.86 kg/liter (GREET 1.8c [12]).[34] Labor inputs to ethanol production are calculated as total expenditures on energy, labor and capital for ethanol production. Additional calibration details are available in Appendix A.2.

We assume an elasticity of substitution between crude oil and a composite of labor and capital, σ_P, of 0.06. This was selected to approximate a perfectly complementary relationship between crude oil and labor, preventing any unrealistic substitution of crude oil for labor.

Rest of World Crude Supply

We consider only that fraction of crude oil that is used to produce regular gasoline.[35] Therefore, our parametrization of the supply of crude oil, only reflects the share of crude oil that is available for the production of regular gasoline. We use a central elasticity of crude oil supply, η_R, of 0.50. This value is calculated using literature values for the elasticity of world demand and supply for crude oil, -0.03 and 0.04 respectively,[36] and crude oil consumption and production statistics from the EIA [49].

Rest of World Crop Demand

The crop export demand elasticities, η_i in equations (3.10), 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 [50].

3.4 Emissions Factors

The emissions factors corresponding to the ϕ's in equations (2.12) are (2.13) are presented in Table A.5 and are described in detail below. For each product or activity, we account for the release of three major greenhouse gases, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) measured in units of carbon dioxide equivalents (CO_2e).[37]. 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.

[34] The production of ethanol requires corn inputs of 2.56 kg/liter, however co-products equivalent to 0.7 kg corn are produced with each liter of ethanol (GREET 1.8c [12]).

[35] In practice, less than half (47%) of a barrel of crude oil is used to produce regular gasoline. In addition, after processing crude oil into its final products the sum volume of the final products is 5% greater than a barrel, which is known as the processing gain.

[36] Estimates include Greene [46] and [47] for crude oil demand, and Greene [46] and OECD [48] for crude oil supply. We note that our elasticities are conservative estimates from the literature.

[37] We use global warming potentials from IPCC Third Assessment Report [51] to calculate CO_2e.

As a result, our emissions system boundary is slightly more restrictive that that of earlier lifecycle analysis studies (see for example [52], [11], [10]), but consistent with the US EPA [16].

Gasoline

The lifecycle emissions of gasoline, ϕ_G, are 3.0 kgCO_2e/liter, which is the baseline lifecycle emissions for US gasoline estimated by NETL [21]. This factor was estimated for US EPA for use in the Regulatory Impact Analysis [16] of the RFS and in the RFS Final Rule [53]. The sources of emissions include: crude oil extraction, transport and refining, the transportation and distribution of finished gasoline and tailpipe emissions [21]. Refining emissions include the production and consumption of purchased energy, still gas combustion, hydrogen production, flaring and venting.

Ethanol Production and Combustion

The lifecycle emissions from ethanol production, $\phi_{E,M}$, are assumed to be 0.6 kgCO_2e/liter (US EPA [16]). This factor is estimated based on the projected per unit conditional factor demand for natural gas and electricity of a representative natural gas fired dry-mill ethanol plant (US EPA [16]).

Although we assumed that $\phi_{E,C} = 0$ in the analytical model, we measure the release of CH_4 and N_2O from ethanol combustion, which total 0.02 gCO_2e/liter (US EPA [16]). The assumption that the CO_2 released during ethanol combustion is completely offset by carbon uptake during the growing of corn does not hold for other greenhouse gases.

Using 2003 corn yields and our benchmark corn-to-ethanol conversion efficiency, the lifecycle estimate for the amount of land allocated to corn production required to produce one unit of ethanol, $\tilde{A}_y$, is 0.21 ha/1000 liters.[38] The resulting lifecycle emissions of corn ethanol are therefore 1.29 kgCO_2e/liter. Therefore, we estimate that ethanol generates lifecycle emissions savings of 35% relative to gasoline on an energy equivalent basis, which is consistent with estimates for natural gas fired ethanol production (Farrell et al. [10]; Wang [12])

International Crude Oil Consumption

We assume that emissions from non-US crude oil consumption, ϕ_R, are 369 kgCO_2e/barrel. We derive this factor from petroleum consumption and emissions data published by the EIA [49]. Implicit in this factor are EIA assumptions regarding the non-US end uses of crude oil and the average chemical properties of crude oil.[39] We do not consider the lifecycle emissions associated with upgrading crude oil to final consumption products.

[38]We account for a co-product rebate here, following standard lifecycle analysis methods, which assigns a corn equivalence value to the co-products of ethanol production. The co-product rebate reduces $\tilde{A}_y$ by approximately 0.8 ha/1000 liters.

[39]We estimate emissions from crude oil consumption in this manner because: 1) The chemical properties, and therefore the embodied emissions, of crude oil are very heterogeneous; and 2) not all crude is converted into products that are combusted. For example, refineries produce a number of fuels (gasoline, diesel, kerosene among others) as well as other products (asphalt, lubricating oil) in a joint production process. Products such as asphalt are never combusted, so the carbon in these products is not released as CO_2.

Agricultural Production

The production of corn is at least twice as emissions intensive (3.2 mgCO_2e/ha) than each of the other crops we consider (Table A.5). In comparison, hay and wheat production generate only 1.3 mgCO_2e/ha and 1.0 mgCO_2e/ha respectively, while soybean production generates 0.5 mgCO_2e/ha. These crop-specific emissions factors are constructed using our agricultural input and expenditures dataset (discussed above). We consider on-farm sources of emissions, which include agricultural N_2O, energy use and liming, as well as emissions from agricultural input production. A detailed discussion of the assumptions underlying these emissions factors is in Appendix A.3.

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 US EPA [16], 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. Further, the carbon stored in below-ground biomass and soils of CRP land is released within the next 30 years. Consistent with standard practice (see for example the US EPA [16]), we amortize total emissions from land use conversion over 30 years. To construct our emissions factor we assume that CRP land is abandoned cropland planted to perennial grasses for 15 years, which store 30.51 mgCO_2e/ha in above and below ground biomass and 37.95 mgCO_2e/ha in soils (Fargione et al. [14]).[40]

World Land Use Change

We assume that the emissions from the expansion of non-US cropland, $\phi_{N,W}$, is 8.0 mgCO_2e/ha (US EPA [16]). This factor includes carbon released from the above- and below-ground biomass and soils of land converted to agriculture, as well as foregone sequestration. We again amortize all emissions over 30 years. See Appendix A.3 for further details. We emphasize that the emissions from world land use change are substantially larger than the emissions from domestic land use change. This is because cropland expansion in the rest of the world is predicted to displace previously undisturbed land cover with large carbon stocks.

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 (See appendix A.3 for more details). The purpose of this calculation is to isolate the world crop supply response without explicitly calculating land use model. We note that other

[40]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 (Barbarika [25]). Also, given the costs of converting forested land to cropland, it is CRP held in grassland that will likely be converted to cropland. If CRP lands containing woody biomass are converted to cropland then emissions due to biomass loss could be much larger.

factors that we do not account for, in particular price induced yield adjustments, may mitigate a portion of the supply response.

4 Results

Intertemporal Dynamics

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

We assume that household income grows at an annual rate of 1 percent.[41] 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 (USDA [54]), we allow exports to grow by 1.13%, 2.70%, 0.21%, and 1.65% for corn, soybeans, wheat, and cotton, respectively.

We allow fuel economy to exogenously increase by 0.22% per year. This trend is based fuel economy projections from the 2002 National Research Council analysis of CAFE standards [55] and vehicle fleet composition from (Bento et al. [44]).

The price of crude oil follows the Reference Scenario projections of the 2008 EIA Annual Energy Outlook [56], increasing monotonically from 63.37$/bbl in 2009 to 73.85$/bbl in 2015.

In 2009 our crop yields match observed average US yields reported by the USDA [24]. For the years 2010-2015, yields for all crops except hay follow USDA projections [57]. These projections are not linear, but in general are monotonically increasing. Relative to the benchmark year of 2003, corn and cotton yields increase by roughly 20% by 2015 while soybean yields increase by 16%. Wheat yields increase only 1% over the same time period. 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 (FSA [28]). Improvements in international crop yields follow USDA projections.

We allow ethanol production technology to improve following US EPA projections [16]. We allow the labor requirements of ethanol production fall by 50% between 2003 and 2015. This improvement is driven by increasing energy efficiency of ethanol production due to a considerable expansion in efficient dry mill ethanol production (US EPA [16]). The corn-to-ethanol conversion ratio also improves monotonically. In 2015, the US average ethanol conversion efficiency is 0.42 liters/kg, which is 6% higher than the 2003 value.

[41] That is to say that we allow $\bar{L}$ to grow at 1% per year.

Scenarios Considered

We consider two counterfactual baselines in our analysis. The *no-policy baseline*, is a counterfactual in which there are no pre-existing ethanol policies. Against this counterfactual baseline we consider three policy regimes. *Scenario 1* considers the impact of adding the VEETC alone. *Scenario 2* considers the impact of the imposing the RFS alone. Finally, *Scenario 3* considers the impact of imposing the RFS jointly with the VEETC.

The *VEETC baseline*, is a counterfactual in which the VEETC is the sole pre-existing ethanol policy. We compare two policy regimes to the VEETC baseline. *Scenario 4* removes the pre-existing VEETC while simultaneously imposing the RFS. *Scenario 5* imposes the RFS on top of the pre-existing VEETC.

In the tables and discussion below, we focus on results for the years 2009, 2012 and 2015. To conclude the results discussion we report the emissions results for all years, 2009 to 2015, in Figure 1.

4.1 Economic Impacts of Policies

Impact of Policies on New Ethanol

Table 1 presents the amount of ethanol consumed under our two counterfactual baselines, as well as the change in ethanol consumption relative to these two baselines, that occur under each policy scenario.

The *no-policy baseline* is provided in the first row of Table 1. The predicted baseline gradually increases over time, from 21.3 billion liters in 2009, to 31.5 billion liters by 2015. This increase is due to several factors, but the two most important are exogenous increases in the price of crude oil and growth in crop yields. The increasing crude oil price makes ethanol a relatively more attractive substitute for regular gasoline, thus driving up the equilibrium quantity of ethanol. Rising crop yields lower crop prices and consequently the marginal cost of producing ethanol, thus driving up the equilibrium quantity of ethanol.

The VEETC (scenario 1), by lowering the marginal cost of ethanol relative to the marginal cost of gasoline, increases the amount of ethanol realized in the economy. It is this wedge of additional consumption that is reported in Table 1. In 2012, for instance, the VEETC increases ethanol consumption by 19 billion liters over the amount predicted under the no-policy baseline.

Scenario (2) illustrates that the RFS also drives up the amount of ethanol used in the economy, relative to the no-policy baseline. In all years the quantity of ethanol mandated by the RFS exceeds the amount that would be produced in the absence of the mandate, that is to say that the RFS is binding for those years. For 2009, comparison of scenarios (1) against (2) demonstrates that the VEETC and RFS achieve parity in promoting additional ethanol in the economy, either policy or generates the same amount of additional ethanol, about 19 billion liters.

Scenario (3) demonstrates that imposing the VEETC in conjunction with the RFS has no additional impact on the amount of ethanol induced in the economy. Again, for 2009 we have parity. While for the later years, given that the RFS imposes an additional increase in ethanol above what is added by the VEETC alone, it is the RFS that is the policy instrument that is determining the amount of ethanol realized in the economy. As a consequence the amount of ethanol added to the economy for the later years under scenarios (2) and (3), is the same, approximately 25 billion liters.

The second baseline, the *VEETC baseline*, is provided in row five. In effect this is the same as appending the VEETC scenario (1) to the no-scenario baseline. As before, rising crude oil prices and crop yields drive up the amount of ethanol realized in the economy from 40.1 billion liters in 2009 to 45.4 billion liters by 2015.

Compared to the VEETC baseline, the RFS is not binding in 2009, and binding in all years thereafter, it is not surprising that replacing the VEETC with the RFS (scenario 4) achieves the same amount of additional ethanol as simply imposing the RFS while continuing the VEETC (scenario 5). Both scenarios show that relative to an economy with a pre-existing VEETC, the RFS drives up the amount of ethanol realized in the economy by 6 billion liters in 2012, and 11 billion liters by 2015.

Impacts on Land Use

Table 1 establishes that each scenario has a positive impact on ethanol consumption, and would therefore be expected to generate greenhouse gas reductions. We start decomposing the sources of leakage by analyzing the impact of each scenario on US and world land use.

The top three panels of Table 2 report the allocation of US agricultural land to corn, other crops and CRP in the two counterfactual baselines, and the impact of each scenario on the land allocation. The final panel reports the change in world non-agricultural land, which represents world land use change.

In the no-policy baseline, land allocated to corn gradually increases from 30.5 million hectares in 2009 to 31.7 million hectares in 2015. Across the no-policy baseline both land allocated to other crops and held in the CRP fall. The trends in domestic land use are similar in the VEETC baseline.

The primary domestic land use response in each scenario is an expansion in the land allocated to corn production, which is driven by the increased demand for corn for ethanol consumption, The magnitudes of the changes in corn production mirror the changes in ethanol consumption; larger in ethanol consumption lead to larger expansions of corn production. Comparing scenarios (1) and (2) for the years 2012 and 2015, the VEETC has a smaller impact on corn production than the RFS because the VEETC had a smaller impact on ethanol consumption. Further, scenarios (4) and (5), which compare to the the VEETC baseline, have a much smaller percentage impact on corn production than the three scenarios that compare to the no-policy baseline. To accommodate increased corn production, land allocated to the production of other crops and to CRP decreases. Given that the quantity of land in the US is fixed, it follows that scenarios that cause larger increases in corn production must have result in larger reductions in land allocated to the production of other crops and CRP. Again, the reductions in other crops and CRP are much smaller in scenarios (4) and (5) than in the first three scenarios.

Perhaps more important is how the reductions in the production of non-corn crops compares to the reductions in CRP land. Although smaller in terms of percentage relative to baseline, in each scenario the total hectare reduction in other crop production is larger than total hectare reduction in land allocated to the CRP. Focusing on scenario (1), in 2009 other crop production falls by 2.8% relative to the baseline of 81.6 million hectares which is a larger drop than the 7% reduction in CRP land relative to its 13.6 million hectare base. In fact, across all scenarios the reductions in land alloctated to other crops is consistently more than twice the reduction in land allocated to CRP. This illustrates the the primary margin of adjustment in domestic land markets is a shift to corn from other aricultural production rather than an expansion in cropland. This is critical from an emissions perspective because reductions in non-corn crop production reduces emissions, while reductions in CRP generate emissions.

The aggregate world land use response to each scenario is a reduction in non-agricultural land, or equivalently an expansion in world cropland. As with the domestic land use, the magnitude of the world land use response (displayed in the final panel of Table 2) follows the increase in ethanol consumption the results in each scenario. This is because the world land use effect is driven by the linkages between US and the rest of the world through world crop markets. The increased demand for corn due to expanded ethanol consumption results in a reduction in US crop exports. Corn exports fall because the increased demand for corn for ethanol production diverts corn away from being exported. Exports of non-corn crops fall because ethanol policies cause an overall reduction in production to non-corn crops in the US. Reductions in US exports cause an increase in the world price of crops and a supply response by farmers in the rest of the world.

As the overall land use impacts of each scenario are driven by the changes in ethanol consumption, when the RFS binds, the addition or removal of the VEETC will have no impact on land use. Specifically, scenarios (4) and (5) have identical impacts on land use in each year even though the VEETC is absent in scenario (4). Likewise scenarios (2) and (3) have identical land use impacts in 2012 and 2015.

Impacts on Fuel Prices

We next focus on the drivers in leakage in fuel markets. Table 3 highlights the impact of the various policies on the prices realized in fuel markets. The price of the two inputs into blended fuel production, ethanol and gasoline, are reported in panels one and two, while the price of blended fuel is reported in panel three.

Due to the growth in crude oil prices, the price of ethanol under the no-scenario baseline is gradually increasing over time. Against this baseline, the VEETC (scenario 1) unequivocally lowers the price of ethanol realized in the economy, by -19% in 2009 when the baseline price is lower, to -15% in 2015 when the baseline price is higher. Given that the RFS forces fuel blenders to mix more of an input that is increasing in costs, the RFS (scenario 2) drives up the price of ethanol. The increase in ethanol price grows from 14% in 2009 to 34% in 2015, largely in tandem with the increase in the amount of ethanol consumption induced by the policy. Imposing the RFS in conjunction with the VEETC (scenario 3), implies the same price effect in 2009 as in scenario (1), given that the RFS is not binding. However, for the later years in which the RFS is binding, the inclusion of the VEETC acts to soften the price increases induced by imposing the RFS alone. For 2012 this implies a net decline in the price of ethanol of -11%, while for 2015 this implies a net increase in the price of ethanol by 2%.

Compared to the VEETC baseline, maintaining the RFS in isolation (scenario 4) implies a greater price increase than when the RFS is added on top of the pre-existing VEETC (scenario 5).

While the two policy instruments have immediate repercussions with respect to the price of ethanol, the impact of these policies on the price of gasoline and blended fuel is not always clear.

Given that the VEETC is received by fuel blenders, the VEETC operates to shift the fuel blender's input demand for ethanol towards the origin. As a result of changing the relative prices of the two inputs, the fuel blender reduces the amount of gasoline it mixes into each gallon of blended fuel in order to take advantage of the now cheaper alternative, ethanol. This changes the proportion of ethanol going into blended fuel (and in parallel the proportion of gasoline going into blended fuel), which we define here as the *composition effect*. In the case of the VEETC this change in the input mix is determined wholly through the price mechanism—ethanol is now cheaper relative to gasoline, and so the blender demands more of it—and thus is a consequence of the economic equilibrium realized from adding the VEETC to the economy.

In addition to the composition effect, by subsidizing the price of one of the inputs used in the production of blended fuel, the VEETC lowers the marginal cost of producing blended fuel, in effect shifting the supply of blended fuel downward away from the price axis.[42] Consequently, given this lower price, consumers will respond by increasing their total consumption of blended fuel, leading to a secondary *output effect* which, for the case of the VEETC, unequivocally expands the amount of blended fuel realized in the economy.

Given that the composition effect operates to lower the share of gasoline in each gallon of blended fuel, but that the output effect operates to raise the total amount of blended fuel in the economy, it will generally be the case that the amount of ethanol added to the economy as a result of the VEETC will be greater than

[42] By a smaller vertical distance than the VEETC on the demand side, given that this vertical distance is a function of the share of ethanol implied at each increment of the price axis for blended fuel and the VEETC.

the amount by which gasoline falls. Against the no-scenario baseline, the VEETC leads to a fall in the price of gasoline of -4% when the baseline price is low, to -2% when the baseline price is high (scenario 1). Not surprisingly, given that the input prices of both fuels decline under the VEETC (scenario 1), the price of blended fuel also declines from 3% in 2009 to 2% in 2015 (composition effect net of output effect).

While the RFS itself is a *quantity mandate*, specifying the total amount of ethanol that must be blended into blended fuel, in practice, the RFS is imposed as a *share mandate*, specifying the precise amount of ethanol that is to be blended into *each liter* of blended fuel. What this latter representation makes clear is that, since gasoline is the only other input in blended fuel, one less this share standard, is the *implied share quota* on gasoline.[43]

Thus, while the VEETC affects the composition of blended fuel *indirectly* by lowering the prices of one of the inputs used in the production of blended fuel, the RFS *directly* manipulates the composition of ethanol in blended fuel (and in parallel, that of gasoline), irrespective of the resulting impact on the input prices of ethanol and gasoline. The net impact of these dueling price changes and their resulting impact on the marginal cost of blended fuel, however, is not inconsequential as this determines whether the output effect implied by the RFS is positive (as is the case always for the VEETC), or negative. That is to say, whether the RFS increases the amount of blended fuel realized in the economy, or decreases it.

While the share mandate on ethanol operates to increase the equilibrium price of ethanol, and thus raise the marginal cost of producing blended fuel, the implied share quota on gasoline operates to decrease the equilibrium price of gasoline, and thus to lower the marginal cost of producing blended fuel. Which of these competing price effects dominates the final realized equilibrium price of blended fuel depends on the relative slopes of the two input supply functions, which, given our assumptions of CRTS in both the production of ethanol and regular gasoline, are largely determined in our model by the supply elasticity of corn, and the supply elasticity of crude oil, respectively.

If the slope of the input demand function for gasoline is steeper than the slope for ethanol (reflecting the fact that the elasticity of crude oil supply is relatively less elastic than the supply elasticity for corn), than a small decline in the amount of gasoline demanded will result in a greater price decline, than the price increase resulting from an equally small increase in the amount of ethanol demanded. In addition, given that gasoline is the dominant input in blended fuel production, in order for the price of blended fuel to increase as a result of the RFS, the percentage increase in the price of ethanol must be more than ten times larger than the percentage decrease in the price of regular gasoline. Thus, while the RFS alone (scenario 2) drives up

[43] We are intentionally precise with our language here. We use the term 'share mandate' to refer to quantity requirements that are intended to characterize the minimum amount of ethanol in each gallon of blended fuel, and 'implied share quota' to characterize the fact that the legislation indirectly restricts the maximum amount of gasoline that can be blended into each gallon of blended fuel.

the price of ethanol by 14 to 34% relative to the no-scenario baseline, the fall in the price of regular gasoline is from -4 to -6%, and thus the net effect is a decline in the price of blended fuel of about 1%.

In scenario 3 the fall in the price of gasoline induced by the implied share quota is roughly the same as that induced by the RFS alone (scenario 2), or -4 to -5%. However, given that imposing the RFS alongside the VEETC (scenario 3) considerably softens the increase in the price of ethanol induced by the RFS (in fact, recall that this leads to a decline in the price of ethanol for 2012) when the RFS is binding, as well as the fact that the share of gasoline is ten times that of ethanol, the net effect is dominated by the fall in the price of gasoline. As a consequence the price of blended fuel falls by -3% (scenario 3). This is is roughly two to three times the fall induced by the RFS alone (scenario 2).[44]

Turning to the VEETC baseline, the disparity between imposing the RFS while removing the VEETC (scenario 4) and imposing the RFS in on top of the pre-existing VEETC (scenario 5) becomes even more apparent. As the third panel shows, the price of blended fuel actually *increases* the price of blended fuel by 1% when the RFS is binding (scenario 4). This arises due to the fact that the increase in the price of ethanol by 51 to 59% exceeds by more than ten times the fall in the price of gasoline of -2 to -3%. This is in sharp contrast to simply imposing the RFS on top of the pre-existing VEETC (scenario 5), which implies a decline in the price of blended fuel of roughly half a percentage point, relative to the VEETC baseline. In this case, the VEETC offsets the increase in the price of ethanol induced by the RFS, effectively cutting the increase in the price of ethanol down to 10 to 20%, when the RFS is binding (scenario 5). This is less than ten times the fall in the price of gasoline of -1.3 to -2.5%, and thus the net effect is for the price of blended fuel to fall.

Impacts on Fuel Quantities

Table 4, which presents the impacts of the various policies considered on the amount of the various fuels realized in the economy. The first panel on ethanol quantities reiterates the results from Table 1, here reporting the wedge of additional ethanol realized under each policy scenario in percentage terms, relative to the pertinent baseline.

The second panel reports the impacts of the various policies on the amount of gasoline realized in the economy. The magnitudes reported here parallel the impacts of the various policy scenarios on the price of regular gasoline discussed earlier. Given that the RFS alone (scenario 2), raises the price of ethanol by a greater degree than when the VEETC ameliorates the price consequences of the RFS (scenario 3), the

[44] In fact, when one normalizes the percentage fall in the price of blended fuel by the amount of additional ethanol realized due to the policy from Table 1, we see that scenario 3 drives down the price of blended fuel per unit of additional ethanol by an amount that is greater than the same for the VEETC alone (scenario 1). For 2012, for instance, this implies $\frac{-2.4\%}{18.9} = -0.13\%$ per billion liters of new ethanol, for the VEETC alone (scenario 1), and $\frac{-3.4\%}{24.3} = -0.14\%$ per billion liters of new ethanol for the RFS plus VEETC (scenario 3). This is not surprising. The VEETC neutralizes the price increase in ethanol induced by the RFS, leaving only the second policy implied by the RFS to drive the fall in the price in blended fuel.

implied impact on the price of blended fuel implies a greater output effect under scenario 3, than under scenario 2. Since blended fuel used expands when the VEETC is paired with the RFS (scenario 3), the displacement of gasoline is smaller, only -2% relative to the no-scenario baseline, than when the RFS is imposed alone (scenario 2), which results in a displacement of gasoline of -3%. Against the VEETC baseline similar patterns emerge. When the RFS replaces the VEETC (scenario 4), gasoline use falls by -1.5 to -2.2% for a binding RFS. When the RFS is imposed on top of the pre-existing VEETC (scenario 5), fewer liters of gasoline are displaced, -0.8 to -1.5%.

The third panel presents the impacts of the various policies on the amount of blended fuel realized in the economy. Against the no-scenario baseline, the VEETC alone (scenario 1) induces a larger increase in blended fuel consumption of 0.8 to 1.2%, than the RFS alone (scenario 2), 0.5 to 0.6%; this is despite the fact, that the amount of ethanol induced by the RFS is the same or greater than that induced by the VEETC. A beneficial output effect (one that reduces blended fuel consumption, and consequently works in a direction to further reduce emissions) is largely driven by the rate at which the price of ethanol increases relative to the decrease in the price of gasoline. In fact, given that ethanol is roughly one-tenth of a liter of blended fuel, this rate needs to be greater than 10, in order for the price of blended fuel to increase, and the total amount of blended fuel realized in the economy to fall, e.g. $\left|\frac{\%\Delta P_E}{\%\Delta P_G}\right| > 10$, implies $\%\Delta P_F > 0$, and thus also $\%\Delta F < 0$. However, when the VEETC is paired with the RFS (scenario 3) the increase in the price of ethanol is reversed or substantially muted, leaving the fall in the price of gasoline to be the primary driver leading to the fall in the the price of blended fuel. As a consequence, it is not surprising that blended fuel increases by 1.2 to 1.4% when the RFS is paired with the VEETC (scenario 3).[45]. Again, comparison against the VEETC baseline further highlights the sharp contrast in the output effect induced by the two policy instruments. Removing the VEETC while simultaneously imposing the RFS (scenario 4) implies a beneficial output effect, that is a fall in the amount of blended fuel realized in the economy by -0.5%. Again, allowing the VEETC to continue alongside the RFS (scenario 5), implies an increase in the amount of blended fuel realized in the economy by 0.1 to 0.2%, when the RFS is binding. Thus, from the perspective of current policy, if leakage is highly correlated with a large positive output effect in fuel markets, then allowing the VEETC to continue alongside the RFS is clearly sub-optimal.

[45]In fact, scenario 3 implies a larger increase in blended fuel than scenario 1, the VEETC alone. This is not surprising. First, imposing the RFS implies a larger ethanol wedge than when imposing the VEETC alone. Secondly, for 2009 and 2012, the RFS plus VEETC leads to a decline in the price of ethanol, which amplifies the fall in the price in gasoline induced by the fall in the implied share quota for gasoline, thus amplifying the impact on blended fuel beyond that which would be possible with the VEETC alone. For 2015, however, adding the VEETC alongside the RFS does not lead to a fall in the price of ethanol, rather increases it slightly, thus softening the impact on blended fuel relative to the VEETC. This is clear when one controls for the first point, by normalizing the increase in blended fuel by the wedge in ethanol induced by the various policies. For 2012, for instance, for every 1% increase in new ethanol, blended fuel increases by 0.0135 % under the VEETC alone (scenario 1), and by 0.0148 for the VEETC plus RFS case (scenario 3). However, by 2015, when the RFS plus VEETC implies a slight increase in the price of ethanol, each 1% increase in new ethanol implies an increase in blended fuel by 0.0172 % for the VEETC alone (scenario 1), and 0.0162%, for the VEETC plus RFS (scenario 3).

Table 5 presents the impact of various policy scenarios on crude oil markets. We note that the price impacts of these policies almost perfectly parallel those for gasoline, given the assumptions of the numerical model, and thus are omitted here. Given that all of the ethanol policies considered here lower the price of gasoline and thus crude oil, each reduction in US crude oil consumption corresponds to an opportunity to expand crude oil consumption by the rest of the world. This price impact permeates only through the demand side of the world crude oil market. Against the no-scenario baseline, the VEETC alone (scenario 1) implies a decline in US demand for crude oil of -1 to -2%. The RFS either alone or in conjunction with the VEETC, implies a fall in US demand for crude oil of -2 to -3%. When compared against the VEETC baseline, the RFS (scenarios 4 and 5) imply a reduction in US demand for crude oil of -1 to -2%, again given the smaller amount of new ethanol added to the economy relative to the pre-existing VEETC. Given that the amount of crude oil demanded by the ROW is considerably greater than that used by the US, these policies imply an increase in ROW demand for crude oil of 0.1% against the no-scenario baseline, and between 0.0 to 0.1%, against the VEETC baseline. In either case, what at first appear to be emissions savings from reducing US crude oil demand are partially reversed by a multiplier effect with regard to ROW demand for crude oil, that is largely determined by the relative slopes of the two demand functions, controlling for the supply of crude oil from the ROW.

4.2 Greenhouse Gas Emissions

Intended Emissions Savings

Our emissions results are presented in Tables 6 and 7. Each component of leakage from Equation (2.13) is reported as a percentage of intended emissions savings.

The intended emissions savings of each scenario map directly from the change in ethanol consumption induced by that scenario (Table 1). This follows from Equation (2.13) which illustrates that in our framework, the intended emissions savings a policy is equal to the increase in ethanol consumption induced by the policy multiplied by the lifecycle emissions savings of ethanol relative to gasoline (which are roughly 0.85 kgCO_2e/liter). In 2009, the RFS is not binding relative to the VEETC baseline, so scenarios (4) and (5) have no impact on emissions. Therefore, to compare across scenarios, we focus on 2012. Scenarios (2) and (3), result in the largest intended emissions savings of roughly 20.5 tgCO_2e. Scenario (1) results in intended emissions savings of a similar, but smaller, magnitude, 16 tgCO_2e. In contrast, scenarios (4) and (5), which use the VEETC baseline as a counterfactual, only result in intended emissions savings of approximately 5.0 tgCO_2e.

For scenarios (2) through (5), intended emissions savings increase between 2012 and 2015 because the quantity of ethanol mandated by the RFS expands through 2015. The increase in intended emissions savings for scenarios (2) and (3) is small, but is nearly a doubling for scenarios (4) and (5). The intended emissions savings in scenario (1) decrease slightly over this time as the impact of the VEETC on ethanol consumption becomes smaller.

Land Market Leakage

Table 6 reports total land market leakage and decomposes total leakage in land markets into four sources following equation (2.13). The first three sources, corn production, other agriculture and domestic land use change comprise the total leakage in domestic land markets (the "Domestic Land" term in equation (2.13)). The fourth source of land market leakage is world land use change. Consistent with others (Searchinger et al. [15] and US EPA [16]), we find that biofuel policies are subject to considerable leakage in land markets, ranging from 50% to 85% of intended emissions savings.

Total land market leakage is most severe in the scenarios that compare to the VEETC baseline. In 2012, land market leakage in scenarios (4) and (5) offset approximately 71% of 5 tgCO_2e of intended emissions savings. In comparison, total land market leakage in 2012 for scenarios (2) and (3) was between 66% and 67% of roughly 20.5 tgCO_2e. This pattern also holds for 2015. Land market leakage in scenarios (4) and (5) increased to 85% of 9.6 tgCO_2e intended emissions savings, while land market leakage in scenarios (2) and (3) is 65% of a approximately 22 tgCO_2e.

When comparing scenarios that use the same baseline, land market leakage is more severe in scenarios that have large intended emissions savings, or equivalently larger impacts on ethanol consumption. For example, in 2012 land market leakage in scenario (1), 63.4%, is smaller than total land market leakage in scenarios (2) and (3), approximately 66%. In 2015, the relationship is simlar.

Following directly from the land use results, if the RFS is binding in a given year, then the VEETC will have no impact on land market leakage. For example, scenarios (4) and (5) differ only by whether the VEETC is imposed and result in the same magnitude total land market leakage in both 2012 and 2015. Comparing scenario (2) to scenario (3) in each year further strengthens this point. In general, land market leakage is insensitive to whether it is the RFS or VEETC driving the expansion in ethanol consumption.

World land use change generates the bulk of total land market leakage. In 2012, it accounts for a leakage of around 70% for scenarios (1), (2) and (3). In the same year, world land use change in scenarios (4) and (5) was over 80%. In scenarios (4) and (5) this leakage increases between 2012 and 2015 because the impact of the RFS on ethanol consumption expands over this time. Domestic land use change, or the conversion of CRP to crop land, is the other source of positive leakage. However, the leakage from domestic land use change is considerably smaller than world land use change, ranging from 8% and 14% of intended emissions savings. The difference in leakage from these two sources is driven by the emissions factors; the emissions consequences of converting one unit of non-agricultural land to agricultural production are approximately 3 times greater in the rest of the world than in the US.

In all scenarios, both domestic corn and other domestic crop production are sources of negative leakage. In 2012, leakage from domestic corn production ranges between -5.4% to -10% of intended emissions savings. Leakage from corn production is negative because the additional land allocated to corn production per unit ethanol used to calculate intended emissions savings overestimates the expansion in corn production relative to our model's prediction. Specifically, referencing equation (2.13), $\tilde{A}_Y \frac{dE}{d\Omega} > \frac{dA_Y}{d\Omega}$ in all scenarios and years. A more substantial negative leakage indicates a larger overestimate.

This analysis of emissions from corn production illustrates a key weakness of lifecycle analysis, in particular when applied to large scale policies. The lifecycle calculation of the expansion in land allocated to corn production relies only the yields of corn production and the per unit ethanol factor demand for corn (see discussion in section 2.2). This calculation does not account for potential adjustments in agricultural prices due to increased corn demand, or substitute end uses for corn, such as food production and exports. Increased demand for corn due to expanded ethanol production will cause the price of corn to increase relative to other crops. In response, the consumers of agricultural products substitute away from corn to other crops. The result is an increase in corn production that is less than the corn required to produce the ethanol added by the policy. Our predicted increase in land allocated to corn production is smaller than the lifecycle prediction, specifically because our framework explicitly allows for this margin of adjustment.

Leakage from other domestic agricultural production is always negative because the amount of land allocated to non-corn agricultural production falls in each scenario. Consistent across all scenarios and years, leakage from other domestic agriculture is between -11% and -14% of intended emissions savings. Interestingly, the negative leakage from other agriculture nearly offsets the positive leakage from domestic land use change, even though the per hectare emissions consequences of domestic land use change are greater than the emissions savings from displacing non-corn agricultural production (see Table A.5). Leakage from non-corn crop production and domestic land use are similar in absolute magnitude because the reductions in non-corn cropland in each scenario are larger than the reductions in land allocated to CRP.

Fuel Market Leakage

Table 7 reports the two total emissions from fuel markets as a percentage of intended emissions savings. Total leakage is further decomposed according to equation (2.13) in to leakage in the domestic fuel market and the world crude oil market.

Leakage in the world crude oil market is positive in all scenarios, accounting for a leakage at least 55% of intended savings. This follows that the world consumption of crude oil increases in each scenario (Table 5).

In a given year, leakage in world crude markets is greater in scenarios that do not impose the VEETC. For example, scenario (4) results in larger crude leakage than scenario (5) in both 2012, 74% relative 59.3%, and 2015, 67.7% relative to 61%. Likewise, scenario (2) results in a marginally higher leakage in ROW crude markets than scenario (3) in each year. Leakage in world crude oil markets is large because of the size of world crude oil market in comparison with the domestic fuel market. Even small reductions in the world price of crude oil generate emissions that are large relative to the intended emissions savings of biofuel policies.

Leakage in the domestic fuel market is negative in scenario (4), but is positive in all other scenarios, mirroring the changes in blended fuel consumption reported in Table 4. Domestic fuel market leakage is largest in scenarios (1) and (3), both of which impose the VEETC. In 2009, scenario (1) is subject to leakage of 68%, while scenario (3) generates leakage of 87%. In 2012 and 2015, domestic fuel market leakage in both of these scenarios is greater than 79%. Domestic fuel market leakage in scenarios (2) and (5) is positive, but notably smaller in percentage terms than scenarios (1) and (3). In scenarios (2) and (5) domestic fuel market leakage is between 25% and 30% of intended emissions savings. In scenario (4), domestic fuel market leakage is -170% in 2012 and -74.3% in 2015. This negative leakage occurs because imposing the RFS while removing the VEETC results in decreased blended fuel consumption.

The domestic fuel market can be a large source of leakage, either positive or negative, because the per liter emissions from gasoline is on the order of three times greater than the per liter intended emissions savings of corn ethanol. Thus, when converted to emissions, small changes in blended fuel consumption are magnified relative to increases in ethanol consumption.

Unlike total land market leakage, the magnitude of total fuel market leakage is largely determined by the presence of the VEETC. In scenario (1), which isolates the impact of the VEETC, total fuel market leakage dominates the intended emissions savings. Total fuel market leakage is 122% in 2009 and increases to 145.3% in 2015. When imposed jointly with the RFS, the VEETC serves only to increase total leakage in fuel markets. Comparing scenario (3) to scenario (2) demonstrates that had the VEETC never been implemented, total fuel market leakage due to the RFS would decrease from approximately 140% of intended emissions savings to 90% of intended savings for each year reported. This is because imposing the VEETC increases leakage in domestic fuel markets.

The difference between scenarios (5) and (4) illustrates the impact of removing the pre-existing VEETC. In 2012, total fuel market leakage due to the RFS is 86% of intended emissions savings if the pre-existing VEETC is maintained. However, if the VEETC is removed, total fuel market leakage due to the RFS is -96% of intended emissions savings. That is, fuel market adjustments generate emissions reductions that are equal in magnitude to the intended emissions savings of the policy. The negative leakage in domestic fuel markets dominates the positive leakage in world crude markets. In 2015, removing the VEETC reduces total fuel market leakage from 87% (scenario (5)), to -6.6% (scenario (4)).

Do Corn Ethanol Policies Reduce Emissions?

In each panel of Figure 1 we compare the intended emissions savings (solid black line with square markers) to the emissions savings after accounting for leakage (dotted grey line) of a given scenario, for the years 2009 to 2015.[46] Net emissions after accounting for land market leakage (dotted gray line with circular markers) and fuel market leakage (dotted gray line with triangle markers) are also plotted. The horizontal axises measure the increased ethanol consumption due to the policy in a given year. Thus, moving along the horizontal axis illustrates an increase in the realized impact of the policy on ethanol consumption, and not necessarily a progression through time.[47] Positive leakage is illustrated by the leakage curve lying above the intended emissions curve. A leakage curve above the horizontal axis indicates that leakage totally offsets the intended emissions savings and that the given scenario has a positive net impact on greenhouse gas emissions.

If both land and fuel market leakage is considered, carbon leakage easily outweighs intended emissions savings in scenarios (1), (2), (3) and (5). The net increase in emissions is most severe in the scenarios that impose the VEETC (1) and (3). For these scenarios, the actual change in emissions is roughly equal to the negative of intended emissions savings. This relationship holds even as the increased consumption of ethanol due to policy grows larger. For example, a 16 billion liter expansion in ethanol consumption driven solely by the VEETC (scenario 1) results in a net increase in emissions of 13 $tgCO_2e$, while the intended emissions savings were 14 $tgCO_2e$. A 19 billion liter increase in ethanol consumption results in emissions of 15.8 $tgCO_2e$ while the intended emissions savings of that increase are 16 $tgCO_2e$. Likewise, in scenario (3) the intended emissions savings of a 22 billion liter expansion in ethanol consumption are 19 $tgCO_2e$, but after accounting for leakage, the net impact on emissions is an increase of 20 $tgcCO_2e$. A 25 billion liter increase in ethanol consumption results in intended emissions savings of 22 $tgcCO_2e$ but a net increase in emissions of 23 $tgCO_2e$.

In scenarios (1) and (3), the contribution of fuel market leakage to total leakage is greater than the contribution of land market leakage. In fact, fuel market leakage alone dominates the intended emissions savings; the fuel market leakage curve lies above the horizontal axis. If only land market leakage is considered, then both scenarios would generate reductions in greenhouse gas emissions.

Scenarios (2) and (5) have a smaller positive impact on net emissions than scenarios (1) and (3). A 22 billion liter expansion in ethanol consumption in scenario (2) results in a net emissions increase of 10

[46] The line markers indicate a specific yearly observation.

[47] We do allow for dynamic trends in our simulations. As a result, the curves in Figure 1 do not completely isolate the effect of the scale of the policy on leakage.

$tgCO_2e$, compared to intended emissions savings of 19 $tgCO_2e$. In scenario (5), a 6 billion liter increase in ethanol consumption causes an emissions increase of 2.8 $tgCO_2e$, while the intended emissions savings of this increase in ethanol consumption were 5 $tgCO_2e$. In both of these scenarios, the contributions of fuel market and land market leakage to total leakage is roughly equal. Further, neither land market leakage nor fuel market leakage is alone large enough to completely offset the intended emissions savings, as both land and fuel market leakage curves falls below the horizontal axis.

Scenario (4) does generate emissions savings, after accounting for leakage, because negative leakage in fuel markets largely offsets the positive leakage in land markets (the total leakage curve always falls below the horizontal axis). However, fuel market leakage becomes less negative as the policy's impact on ethanol consumption increases because the policy causes a smaller increase in the price of blended fuel. Thus, total leakage is negative for smaller increases in ethanol consumption, but positive for larger increases.

For increases in ethanol consumption less than approximately 6 billion liters, total leakage is negative. Thus, the emissions reductions generated by scenario (4), after accounting for leakage, are larger than the intended emissions savings. For example, the net emissions reductions from a 4 billion liter increase in ethanol consumption are 7.5 $tgCO_2e$ even though intended emissions reductions are only 3 $tgCO_2e$. This occurs because negative fuel market leakage is considerably larger in absolute value than the positive land market leakage.

Increases in ethanol consumption greater than 6 billion liters result in positive total leakage, as positive land market leakage starts to dominate the negative fuel market leakage. For an 8 billion liter increase in ethanol consumption emissions reductions are 4 $tgCO_2e$ while intended emissions savings are 6.5 $tgCO_2e$. Fuel market leakage continues to fall (become less negative) with larger increases in ethanol consumption. A 10 billion liter increase in ethanol consumption generates a 3 $tgCO_2e$ reduction in emissions, compared to intended emissions savings of 8 $tgCO_2e$.

5 Conclusion

This paper applies the insights of the carbon leakage literature to study the emissions consequences of biofuel policies. We develop a simple analytic framework to decompose the intended emissions impacts of biofuel policy from four sources of carbon leakage: domestic fuel markets, domestic land markets, world land markets and world crude oil markets. A numerical simulation model illustrates the magnitude of each source of leakage for two current US biofuel policies: the Volumetric Ethanol Excise Tax Credit and the Renewable Fuel Standard.

Consistent with prior studies, we find that US biofuel policies can lead to considerable carbon leakage in both domestic and international land markets. In addition, we find that by altering the relative prices of fossil fuels, biofuel polices also generate leakage in fuel markets. Critically, fuel market leakage is dependent upon the biofuel policies being analyzed. For example, we find that for policy scenarios that include the VEETC, either alone or in conjunction with the RFS, fuel market leakage may actually exceed land market leakage. When considering the RFS alone relative to no prior ethanol policies, fuel market leakage is less than the other policy combinations considered, but is still positive. On the other hand, if the RFS were to replace the pre-existing VEETC, we predict that the realized price of blended fuel would increase, and hence lead to a decline in fuel market leakage. In this case, negative fuel market leakage can offset a sizable portion of the positive leakage in land markets.

In the presence of both land and fuel market leakage, current US biofuel policies are unlikely to reduce greenhouse gases. Four of the five policy scenarios we consider lead to increases in greenhouse gas emissions. That is, total leakage was greater than 100%. The single scenario that generates emissions savings, the removal of the VEETC in conjunction with a binding RFS, only does so because negative leakage in the domestic fuel market offset the remaining positive sources of leakage.

A Appendix

A.1 Derivation of Marginal Emissions Formula

To derive the marginal emissions formula we totally differentiate total emissions with respect to the biofuel policy, Ω:

$$\frac{d\Phi}{d\Omega} = \phi_G \frac{dG}{d\Omega} + \phi_{E,M} \frac{dE}{d\Omega} + \phi_Y \frac{dA_Y}{d\Omega} + \phi_Z \frac{dA_Z}{d\Omega} + \phi_{N,D} \frac{dA_{N,D}}{d\Omega} + \phi_{N,W} \frac{dA_{N,W}}{d\Omega} + \phi_R \frac{dR_W}{d\Omega} \tag{A.1}$$

where:

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

Adding the following terms to Equation (A.1)

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

recognizing that

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

and rearranging terms yields Equation (2.13). The equations in (A.3) allow for the decomposition of lifecycle emissions and leakage. Equation (A.4) follows from equation (A.2).

A.2 Data and Calibration

Ethanol Production

To construct 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 were 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 US EPA [16].

To calculate the net of co-product corn required to produce ethanol, we use the quantity of each co-product produced per liter of ethanol reported in GREET 1.8c [12].

Labor inputs to ethanol production are calculated as total expenditures on energy, labor and capital for ethanol production. Following Farrell et al. [10], we assume that the energy requirements of ethanol production are 13.2 MJ/liter, which represents a combination of natural gas, coal and electricity. Average expenditures on labor and capital for ethanol production are assumed to be 0.0053 $/liter and 0.063 $/liter. These values are consistent with values reported by an industry survey (Shapouri and Gallagher [58]).

Consistent with the US EPA [16], 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.[48]

A.3 Emissions Factors

Ethanol Production

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 (US EPA [16]). 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.

Agricultural Emissions

N_2O emissions from agricultural production are calculated using methods and default parameters from the IPCC Guidelines for National Greenhouse Gas Inventories [59]. These methods map nitrogen additions to agricultural soils, from synthetic fertilizers and crop residues, to N_2O emissions.[49] 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 [59].

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 [12]. 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

[48] 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 [58]).

[49] The IPCC methods also consider N inputs from synthetic and organic fertilizer, manure, sewer sludge and crop residues. In the US, nitrogen inputs, and therefore N_2O emissions, from organic fertilizer and sewer sludge are small and are therefore not considered [2].

assume that all carbon in lime applied to agricultural soils is converted CO_2 [59].

We use GREET 1.8c [12] 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 nitrogen production emissions factor is 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 (ERS [60]). This emissions factor include the emissions from producing the feedstock to fertilizer production (primarily natural gas) as well as the emissions from the production and transportation of the fertilizer itself. We use an emissions factor for the production of phosphate fertilizer of 1.04 kgCO_2e per kg nutrient P. This factor includes the production, processing and transportation of sulfuric acid, phosphoric rock and phosphoric acid. Our emissions factor for the production of potassium fertilizer, which includes only the emissions from production and transportation of potassium oxide (K_2O), is 0.69 kgCO_2e/kg nutrient K. The lifecycle emissions of agricultural lime production are 0.63 kgCO_2e/kg lime and present the net emissions from mining, production and transportation, . We use an emissions factor for the production of pesticide, 21.9 kgCO_2e/kg pesticide, that represents the weighted average emissions from the production of four herbicides and a general insecticide.[50]

World Land Use Change

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 [16].[51] 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. Due to variability in carbon stored by different ecosystem types, there is considerable heterogeneity in the greenhouse gas emissions consequences of converting different native ecosystems to cropland. For example, tropical forests, on average, have larger carbon stocks than temperate forests or grasslands, and as a result, tropical deforestation releases relatively more greenhouse gases than the conversion of temperate forests or grasslands. Unfortunately, these details fall outside of our modeling framework. It follows that our model will be unable to capture how different policy instruments affect international land use conversion patterns. However, we consider only corn ethanol policies and do not suspect that the patterns of land use conversion

[50] Crop specific shares of herbicide and insecticide to total pesticide are calculated from USDA data [41]. 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.

[51] The EPA analysis [16] 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.

will vary considerably across these policies.

The share of reduced US exports of crop i replaced by cropland expansion in the rest of the world is given by:

$$\gamma_{ROW,i} = \frac{-\eta_{S,i}^{ROW} S_i}{\eta_{D,i}^{ROW} D_i - \eta_{S,i}^{ROW} S_i} \tag{A.5}$$

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 elasticity database [61] and the supply and demand quantities are 2003 values reported by the USDA [54].

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Tables

Table 1: Impact of Policies on Domestic Ethanol Consumption - Billion Liters

	2009	2012	2015
No-Scenario Baseline	21.3	25.7	31.5
(1) VEETC	18.8	18.9	14.6
(2) RFS	18.6	24.5	25.4
(3) RFS + VEETC	18.8	24.3	25.3
VEETC Baseline	40.1	43.9	45.4
(4) RFS	0.0	5.7	11.3
(5) RFS+VEETC	0.0	6.1	11.4

Table 2: Impacts of Policies on Land Use - Million Hectares

	2009	2012	2015
Corn			
No-Scenario Baseline	30.5	30.8	31.7
(1) VEETC	10.7%	10.4%	5.4%
(2) RFS	10.5%	13.6%	11.3%
(3) RFS + VEETC	10.9%	13.6%	11.3%
VEETC Baseline	33.7	33.9	33.3
(4) RFS	0.0%	2.9%	5.8%
(5) RFS+VEETC	0.0%	3.2%	5.8%
Other Crops (Soybeans, Hay, Wheat, Cotton)			
No-Scenario Baseline	81.6	81.3	80.7
(1) VEETC	-2.8%	-2.8%	-1.8%
(2) RFS	-2.7%	-3.7%	-3.5%
(3) RFS + VEETC	-2.9%	-3.7%	-3.5%
VEETC Baseline	79.3	79.1	79.3
(4) RFS	0.0%	-1.0%	-1.8%
(5) RFS+VEETC	0.0%	-1.0%	-1.8%
CRP			
No-Scenario Baseline	13.6	13.6	12.9
(1) VEETC	-7.0%	-6.8%	-1.9%
(2) RFS	-7.1%	-8.6%	-6.0%
(3) RFS + VEETC	-7.1%	-8.6%	-5.9%
VEETC Baseline	12.7	12.7	12.6
(4) RFS	0.0%	-1.9%	-4.2%
(5) RFS+VEETC	0.0%	-2.1%	-4.2%
World Non-Agricultural Land (million hectares)[a]			
No-Scenario Baseline	-	-	-
(1) VEETC	-1.5	-1.4	-1.1
(2) RFS	-1.4	-1.9	-2.3
(3) RFS + VEETC	-1.6	-1.9	-2.3
VEETC Baseline	-	-	-
(4) RFS	0.0	-0.5	-1.1
(5) RFS+VEETC	0.0	-0.5	-1.1

[a]Baselines are not calculated.

Table 3: Impact of Policies on Domestic Fuel Prices

	2009	2012	2015
Ethanol (including VEETC) - $/liter			
No-Scenario Baseline	0.35	0.35	0.37
(1) VEETC	-19.4%	-18.9%	-15.1%
(2) RFS	14.1%	22.9%	34.3%
(3) RFS + VEETC	-19.1%	-11.0%	1.7%
VEETC Baseline	0.28	0.28	0.31
(4) RFS	0.0%	51.4%	58.6%
(5) RFS+VEETC	0.0%	10.3%	20.4%
Gasoline - $/liter			
No-Scenario Baseline	0.41	0.43	0.47
(1) VEETC	-3.6%	-2.8%	-2.0%
(2) RFS	-3.8%	-5.1%	-5.6%
(3) RFS + VEETC	-3.6%	-4.8%	-5.4%
VEETC Baseline	0.40	0.42	0.46
(4) RFS	0.0%	-2.2%	-3.4%
(5) RFS+VEETC	0.0%	-1.3%	-2.5%
Blended Fuel (including fuel tax) - $/liter			
No-Scenario Baseline	0.59	0.62	0.66
(1) VEETC	-2.9%	-2.4%	-1.9%
(2) RFS	-1.4%	-1.4%	-1.0%
(3) RFS + VEETC	-2.9%	-3.4%	-3.1%
VEETC Baseline	0.58	0.60	0.64
(4) RFS	0.0%	1.2%	1.2%
(5) RFS+VEETC	0.0%	-0.3%	-0.4%

Table 4: Impact of Policies on Fuel Quantities - Billion Liters

	2009	2012	2015
Ethanol			
No-Scenario Baseline	21.3	25.7	31.5
(1) VEETC	88.0%	73.7%	46.4%
(2) RFS	87.2%	95.4%	80.6%
(3) RFS + VEETC	88.0%	94.6%	80.1%
VEETC Baseline	40.1	43.9	45.4
(4) RFS	0.0%	13.1%	25.0%
(5) RFS+VEETC	0.0%	13.9%	25.1%
Gasoline			
No-Scenario Baseline	445.6	449.1	446.6
(1) VEETC	-1.8%	-1.8%	-1.3%
(2) RFS	-2.4%	-3.1%	-3.3%
(3) RFS + VEETC	-1.8%	-2.3%	-2.4%
VEETC Baseline	437.8	442.5	442.4
(4) RFS	0.0%	-1.5%	-2.2%
(5) RFS+VEETC	0.0%	-0.8%	-1.5%
Blended Fuel			
No-Scenario Baseline	460.7	466.6	467.8
(1) VEETC	1.2%	1.0%	0.8%
(2) RFS	0.5%	0.6%	0.5%
(3) RFS + VEETC	1.2%	1.4%	1.3%
VEETC Baseline	466.1	472.4	472.8
(4) RFS	0.0%	-0.5%	-0.5%
(5) RFS+VEETC	0.0%	0.1%	0.2%

Table 5: Impact of Policies on Crude Oil Markets - Billion Barrels

	2009	2012	2015
Domestic Crude Oil			
No-Scenario Baseline	2.1	2.1	2.1
(1) VEETC	-1.7%	-1.8%	-1.3%
(2) RFS	-2.4%	-3.1%	-3.2%
(3) RFS + VEETC	-1.7%	-2.2%	-2.4%
VEETC Baseline	2.1	2.1	2.1
(4) RFS	0.0%	-1.4%	-2.2%
(5) RFS+VEETC	0.0%	-0.8%	-1.5%
World Crude Oil			
No-Scenario Baseline	24.1	24.9	25.7
(1) VEETC	0.1%	0.1%	0.1%
(2) RFS	0.1%	0.1%	0.1%
(3) RFS + VEETC	0.1%	0.1%	0.1%
VEETC Baseline	24.1	24.9	25.7
(4) RFS	0.0%	0.0%	0.1%
(5) RFS+VEETC	0.0%	0.0%	0.1%

Table 6: Land Market Leakage

	2009	2012	2015
(1) No Policy → VEETC			
Intended Emissions Savings (tgCO_2e)	15.5	16.0	12.6
Land Market Leakage	72.7%	63.4%	45.0%
Corn Production	-6.2%	-5.4%	-22.5%
Other Agriculture	-13.5%	-12.8%	-9.3%
Domestic LUC	14.1%	13.1%	4.5%
World LUC	78.3%	68.6%	72.3%
(2) No Policy → RFS			
Intended Emissions Savings (tgCO_2e)	15.4	20.7	21.9
Land Market Leakage	69.3%	65.8%	64.5%
Corn Production	-6.8%	-5.6%	-14.7%
Other Agriculture	-13.0%	-13.1%	-11.3%
Domestic LUC	14.3%	12.9%	8.0%
World LUC	74.8%	71.5%	82.6%
(3) No Policy → RFS and VEETC			
Intended Emissions Savings (tgCO_2e)	15.5	20.5	21.8
Land Market Leakage	76.8%	67.1%	65.5%
Corn Production	-5.2%	-5.2%	-14.5%
Other Agriculture	-13.9%	-13.2%	-11.4%
Domestic LUC	14.1%	12.9%	8.0%
World LUC	81.8%	72.5%	83.4%
(4) VEETC → RFS			
Intended Emissions Savings (tgCO_2e)	0.0	4.7	9.6
Land Market Leakage	0.0%	72.0%	85.0%
Corn Production	0.0%	-9.8%	-6.8%
Other Agriculture	0.0%	-13.9%	-14.0%
Domestic LUC	0.0%	11.5%	12.6%
World LUC	0.0%	84.2%	93.3%
(5) VEETC → RFS and VEETC			
Intended Emissions Savings (tgCO_2e)	0.0	5.0	9.6
Land Market Leakage	0.0%	70.9%	85.3%
Corn Production	0.0%	-7.3%	-6.7%
Other Agriculture	0.0%	-14.4%	-14.1%
Domestic LUC	0.0%	12.4%	12.6%
World LUC	0.0%	80.2%	93.6%

Table 7: Fuel Market Leakage

	2009	2012	2015
(1) No Policy → VEETC			
Intended Emissions Savings (tgCO_2e)	15.5	16.0	12.6
Fuel Market Leakage	143.8%	135.4%	145.3%
Domestic Fuel	87.4%	79.4%	87.1%
World Crude	56.3%	56.0%	58.2%
(2) No Policy → RFS			
Intended Emissions Savings (tgCO_2e)	15.4	20.7	21.9
Fuel Market Leakage	86.7%	89.3%	88.4%
Domestic Fuel	27.6%	29.1%	25.2%
World Crude	59.1%	60.2%	63.2%
(3) No Policy → RFS and VEETC			
Intended Emissions Savings (tgCO_2e)	15.5	20.5	21.8
Fuel Market Leakage	143.5%	142.4%	139.6%
Domestic Fuel	87.1%	84.2%	78.8%
World Crude	56.4%	58.2%	60.8%
(4) VEETC → RFS			
Intended Emissions Savings (tgCO_2e)	0.0	4.7	9.6
Fuel Market Leakage	0.0%	-95.7%	-6.6%
Domestic Fuel	0.0%	-169.7%	-74.3%
World Crude	0.0%	74.0%	67.7%
(5) VEETC → RFS and VEETC			
Intended Emissions Savings (tgCO_2e)	0.0	5.0	9.6
Fuel Market Leakage	0.0%	85.7%	86.8%
Domestic Fuel	0.0%	26.4%	25.8%
World Crude	0.0%	59.3%	61.0%

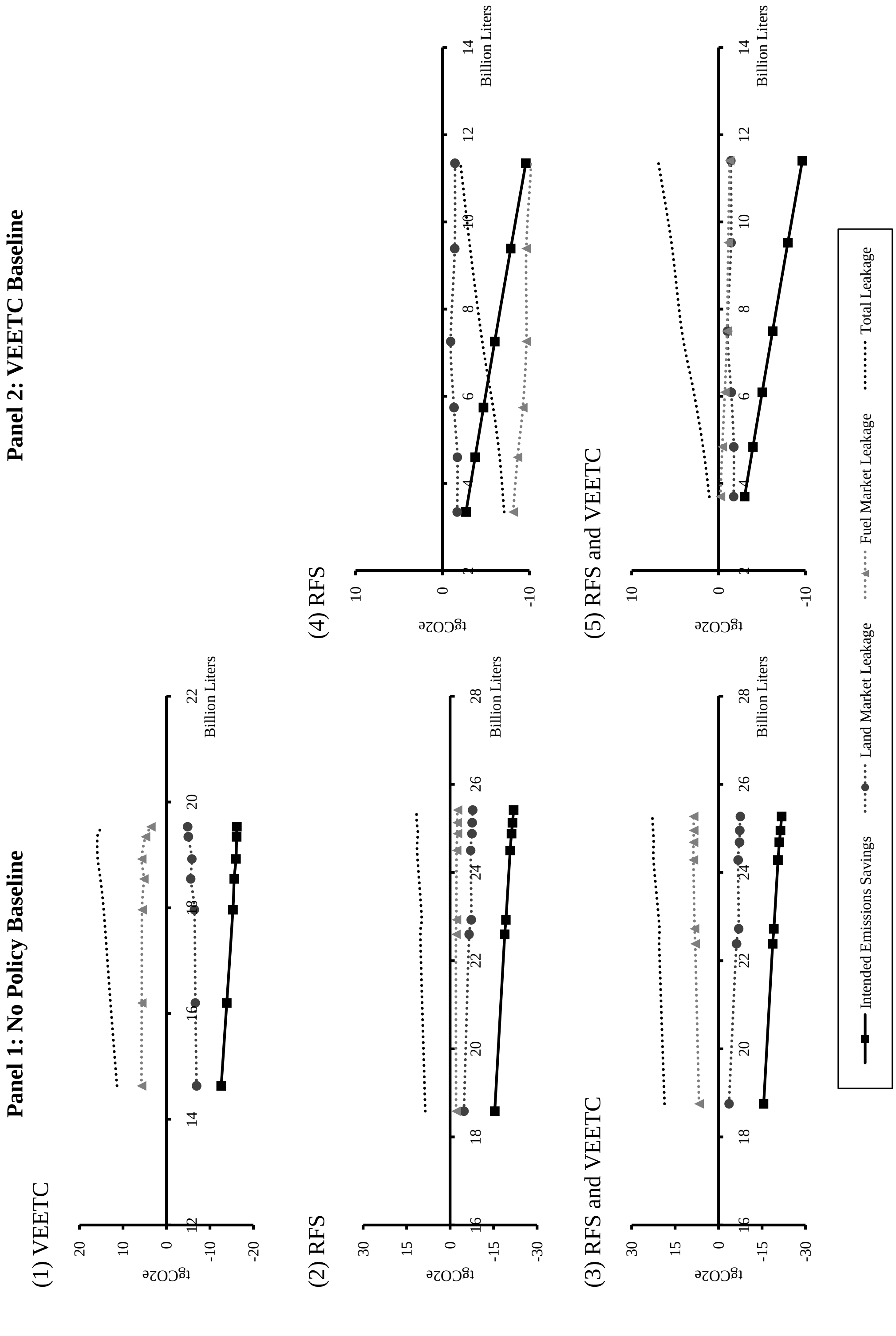

Figure 1: Total Leakage

Table A.1: Description of US Economy in Year of Calibration - 2003

Variable	Value	Source
Economy		
Total Size of Economy (billion $)	$7,667.60	[27]
Net Government Expenditures (billion $)	$2,828.90	[27]
After Tax Value of Labor (billion $))	$3,474.59	
After Tax Value of Capital (billion $)	$1,336.49	[27]
Net Returns from Land Endowment (billion $)	$27.61	[41], [24], [28] [37]
Land-Use Markets		
Total Land Endowment (million hectares)	112.68	[24], [28]
Corn Acres (million hectares)	31.37	[24]
Soybean Acres (million hectares)	29.33	[24]
Wheat Acres (million hectares)	21.47	[24]
Hay Acres (million hectares)	25.65	[24]
Cotton Acres (million hectares)	4.68	[24]
CRP Acres (million hectares)	13.57	[28]
Price of Corn ($/metric ton)	$95.23	[24]
Price of Soybeans ($/metric ton)	$269.62	[24]
Price of Hay ($/metric ton)	$94.22	[24]
Price of Wheat ($/metric ton)	$118.65	[24]
Price of Cotton ($/metric ton)	$1,036.32	[24]
Fuel Markets		
VMT (trillion passenger miles)	2.69	[29]
Blended Fuel (billion liters)	499.97	
Ethanol (billion liters)	10.39	[29]
Regular Gasoline (billion liters)	490.28	[29]
Crude Oil (billion barrels)	5.59	[62], [63], [64]
Price of VMT ($/passenger mile)	$0.19	
Price of Blended Fuel ($/liter)	$0.41	
Price of Ethanol ($/liter)	$0.35	
Price of Regular Gasoline ($/liter)	$0.23	[26]
Price of Crude Oil ($/barrel)	$28.85	[26]
Government Policies		
Labor Tax Rate (%)	36.59%	
Capital Tax Rate (%)	36.59%	
Fuel Tax ($/liter)	$0.10	[65]
Government Rental Payments to CRP ($/hectare)	$114.48	[28]
Factor Prices		
Price of Labor ($/hour)	$9.05	[66]
Price of Capital ($/unit)	$1.03	[67]
Price of Energy ($/ft^3)	$8.40	[26]
Price of Fertilizer ($/ton of NH_3)	$373.00	[42]

Table A.2: Key Parameter Values

Parameter	Value	Source
Households		
Elasticity of substitution, Household Utility, σ_{U1}	0.5	See Text
Elasticity of substitution, Household Utility, σ_{U2a}	0.09	See Text
VMT and Blended Fuel		
Elasticity of substitution, VMT, σ_{U2b}	0.21	See Text
Ratio of fuel cost to total cost of driving	0.4	
Initial Fuel Economy (km/liter)	8.7	[29]
Ethanol		
kilograms corn required per liter ethanol, λ_{E,Y_1}	2.56	[12]
Energy cost required per liter ethanol	$0.06	[10]
Labor cost required per liter ethanol	$0.0053	[58]
Capital cost required per liter ethanol	$0.063	[58]
Regular Gasoline and Crude Oil		
Elasticity of substitution, Regular Gasoline Production, σ_{P1}	0.06	
Elasticity of substitution, Regular Gasoline Production, σ_{P2}	2	
Share of per unit crude oil cost to total cost of gasoline	0.61	[62], [63], [64]
Own price elasticity of crude oil supply (central case)	0.50	
Crude oil yield for regular gasoline	0.47	[62], [63], [64]
Processing gain per barrel of crude oil	0.05	[62], [63], [64]

Values are reported for year of benchmark, 2003. A subset of parameters are updated annually.

Table A.3: Agricultural Expenditure Dataset

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

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

Table A.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†

Elasticity of CRP land with respect to the marginal net returns to cropland is -0.07.
†: [68]; ††: Average of [69] and [70]; ‡: Best guess.

Table A.5: Final Product/Activity Emissions Factors

Gasoline (kgCO_2e/liter)	3.0	
Combustion	2.4	[16]
Production	0.6	[16]
Ethanol (kgCO_2e/liter)		
Combustion	0.02	[16]
Production	0.6	[16]
Crude Oil (kgCO_2e/barrel)	369	[49]
Agriculture (mgCO_2e/ha/year)[1]		
Corn	3.2	
Soybeans	0.5	
Hay	1.3	
Wheat	1.0	
Cotton	1.4	
Land Use (mgCO_2e/ha)		
CRP	2.3	[14], [52]
Rest of World	8.0	[16]

[1]See appendix A.3 for description of calculations. N_2O emissions from agricultural production depend on crop yields and therefore vary by year and policy. Values for scenario (1) in 2015 are reported here.