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

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ABSTRACT

We develop an analytical and numerical multi-market model that integrates land, fuel, and food markets, and link it with an emissions model to quantify the importance of carbon leakage relative to the intended emissions savings resulting from the Renewable Fuel Standard (RFS) for conventional biofuels. The expansion of biofuels mandated by the RFS can increase or decrease GHG emissions depending on the policy regime being evaluated. For example, replacing the Volumetric Ethanol Excise Tax Credit (VEETC) with the RFS, as occurred at the end of 2011 when the VEETC was allowed to expire, would reduce emissions by 2.0 tgCO_2e in 2015 for an expansion of ethanol of 11.4 billion liters. A policy regime consisting of the RFS alone would increase emissions by at least 4.5 tgCO_2e for the same expansion of ethanol. Our findings highlight an important tension between land and fuel market leakage. Policy regimes that result in less land market leakage tend to lead to more domestic fuel market leakage per liter of ethanol added.

Keywords: Climate policy, Multi-market, Carbon leakage, Biofuels, Renewable fuel standards

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1. INTRODUCTION

Although the costs of comprehensive U.S. federal climate legislation, such as a cap-and-trade program, are shown to be rather small (CBO 2009), a variety of political obstacles continue to block its passage. Policymakers have instead relied on sectoral and regional approaches to reduce greenhouse gas (GHG) emissions.[1] A major concern associated with sectoral and regional approaches to climate policy relates to their effectiveness in reducing GHG emissions (Bushnell, Peterman, and Wolfram 2008; Goulder and Stavins 2011). Such approaches are *incomplete*, in that only a subset of polluting sectors or regions are regulated. As a consequence they are likely to

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[1] Examples include the Renewable Fuel Standard which mandates the use of liquid biofuels by the fuel sector, the Corporate Average Fuel Economy (CAFE) standards which mandate minimum fuel economy standards for passenger vehicles and light trucks, and Renewable Portfolio Standards (RPS), which establish state-level targets for renewable energy production by the electricity sector.

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generate *carbon leakage*. Carbon leakage occurs as sectors or regions not covered by the regulation respond to the regulation (directly or indirectly) (Goulder, Jacobsen, and van Benthem 2012). When it comes to sectoral approaches to climate policy, policies that call for the expansion of liquid biofuels have been especially scrutinized by environmental groups and the popular press. Yet, to date very few studies have examined the carbon leakage that results from biofuel policies, and typically only consider a single source of leakage.[2]

The purpose of this paper is to provide comprehensive estimates of carbon leakage from the Renewable Fuel Standard (RFS) for conventional biofuels. The RFS mandates quantities of conventional and advanced biofuels, with each biofuel class defined according to its lifecycle emissions savings relative to gasoline.[3] The current RFS was established in 2007 when the Volumetric Ethanol Excise Tax Credit (VEETC)–the long-standing federal biofuel subsidy–was in place. However, the VEETC was allowed to expire at the end of 2011, leaving the RFS as the primary biofuel support program in the U.S. Our analysis of the RFS explicitly accounts for these changes in policy regime, and reviews the impact of current proposals to eliminate the RFS for conventional biofuels altogether.

This paper addresses three related questions. First, what are the effects of the RFS on land and fuel markets? Second, what is the impact of the RFS on overall GHG emissions, and how does carbon leakage in land and fuel markets cause overall emissions to deviate from the intended emissions savings anticipated by legislators at the time the RFS was passed in 2007? Third, what is the impact of the change in policy regimes and current proposals to eliminate the RFS on overall GHG emissions and leakage due to the RFS?

Several prior studies have examined the emissions impacts of biofuels, although none have simultaneously examined these impacts in the context of past, current, and proposed policy regimes. One strand of the literature relies on lifecycle methods, without reference to a particular biofuel policy. For example, in their seminal work, Farrell et al. (2006) argue that the lifecycle emissions savings of ethanol relative to gasoline are 18%. Many studies recognize that biofuel policies can lead to various multi-market adjustments. However, most develop models to explicitly capture adjustments in *either* fuel (Khanna, Ando, and Taheripour 2008; de Gorter and Just 2009; Rajagopal, Hochman, and Zilberman 2011; Hochman, Rajagopal, and Zilberman 2011; Drabik and De Gorter 2011; Thompson, Whistance, and Meyer 2011; Rajagopal and Plevin 2013) *or* land markets (Searchinger et al. 2008; Hertel et al. 2010; EPA 2010a) either abstracting from adjustments in the excluded markets altogether or assuming constant adjustments and/or emissions factors in the excluded market per unit of biofuel added. For example, Thompson and coauthors (2011) analyze the RFS in a framework that includes world fuel markets and U.S. agricultural markets, but do not link the emissions calculations directly to land market adjustments. Similarly, Rajagopal and Plevin (2013) perform a Monte Carlo analysis to quantify uncertainties in the GHG impacts of biofuel policies using a model of world fuel markets that includes emissions resulting from land market impacts as uncertain parameters that are constant per unit of fuel. The U.S. Environmental Protection Agency's (EPA) Regulatory Impact Analysis of the RFS (EPA 2010a), which is the most comprehensive analysis of the RFS to date, considers the GHG implications of biofuels expansion using

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[2] Our use of the term 'leakage' is somewhat different than that of the literature that examines incomplete regulation. We refer to leakage as the additional GHG emissions that emerge in the economy as a result of market adjustments, relative to intended emissions savings that are calculated using lifecycle analysis (LCA).

[3] Lifecycle analyses (LCA) of GHG emissions attempt to measure all emissions attributable to a product, including the emissions resulting from the production, transportation and consumption of the product of interest, as well as the emissions resulting from the production and transportation of all inputs to the production process.

several sophisticated domestic agricultural and global land use models, but does not quantify the GHG implications that result from adjustments in fuel markets. There are a few studies that consider both land and fuel markets. A set of studies uses the Biofuel and Environmental Policy Analysis Model (BEPAM), which integrates U.S. land and world fuel markets, to analyze first and second generation biofuel policies along a number of dimensions. Chen et al. (2012) examines the changes in domestic land use and emissions resulting from the RFS in 2022. Chen et al. (2011) compares the welfare implications of the RFS, LCFS and a carbon tax in 2030. Huang et al. (2013) examines the welfare and GHG impacts of combining the RFS with a LCFS and carbon price policy. A common feature of the BEPAM analyses is that biofuel policies will cause large expansions in cellulosic ethanol and feedstocks, and relies on assumptions by the EIA regarding future penetration of E-85 automobiles.

Our study differs from earlier work in several ways. First, we develop an analytic and numerical multi-market model that consistently integrates fuel, food and land markets. We link this multi-market model with a sectorally disaggregated emissions model. While some studies (e.g. Chen et al. (2011) and Huang et al. (2013)) also examine the impact of the RFS on total emissions using models that integrate land and fuel markets, our goal is to understand how the emissions consequences of the RFS differ from those intended. We derive an analytical formula that decomposes the overall change in GHG emissions that result from an increase in the RFS into *intended emissions savings* and *carbon leakage*. *Intended emissions savings* are calculated with standard lifecycle methods that reflect the GHG emissions savings resulting from replacing a unit of gasoline with a unit of ethanol, scaled up by the amount of ethanol added to the economy as a result of the RFS. *Carbon leakage* emerges from adjustments in land and fuel markets, both domestic and international, as the RFS impacts key prices. This decomposition is of critical importance to public policy as it directly illustrates the dangers of including LCA metrics in federal legislation as a criteria to select biofuel feedstocks.[4] The analytical formula guides the presentation of our simulation results, and provides a consistent frame of reference for comparing the magnitudes of leakage under various policy regimes and parameter assumptions. Our numerical results uncover a co-dependency between land and fuel market leakage that reflects the underlying economic relationships. For example, policy regimes with less land market leakage emerge because the policy causes a smaller increase in the price of corn per liter of ethanol added. As a result, the price of blend fuel is more likely to decline, resulting in larger fuel market leakage. This suggests that the integration of land and fuel markets is critical for estimating leakage from either market, and for quantifying the total change in GHG emissions due to biofuel policies.

Second, we examine the RFS through the lens of past, current, and proposed policy regimes and therefore are able to shed light on how policy interactions and changes in policy play an important role in the direction and magnitude of leakage due to the RFS. Relative to a baseline that includes the VEETC we consider two policy regimes, one in which the RFS is added to the pre-existing VEETC and a second regime in which the RFS replaces the pre-existing VEETC. We include the VEETC in the baseline in our central analysis because this allows us to understand the emissions implications of the RFS from the perspective of policymakers at the time the RFS was enacted. The first policy regime allows us to isolate the impact of just adding the RFS to the

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[4] Bento and Klotz (2014) show that lifecycle metrics are likely to be misleading measures of the emissions impacts of policy options supporting alternative technologies. They argue that the effectiveness of LCA as a policy tool could be improved if policies were the focus of the analysis and if the economic framework underlying the LCA includes the primary markets impacted by the policy.

economy and reflects the policies in place prior to 2011. The second regime allows us to isolate the impact of replacing the VEETC with the RFS–jointly removing the VEETC while imposing the RFS–and reflects the policies in place from the end of 2011. To understand the implications of current legislative proposals to eliminate the conventional RFS entirely, we consider a third policy regime that examines the impact of adding the RFS to a baseline without the VEETC in place.

Third, by focusing on the RFS for conventional biofuels through 2015 our estimates of the emissions resulting from the RFS will be unencumbered by assumptions regarding second generation biofuels. We are able to safely ignore second generation biofuels because mandated and realized volumes of second generation biofuels are likely to be negligible over the time horizon of our study.[5] An analysis of the RFS through 2022 would require strong assumptions to dictate the emergence of second-generation biofuels, such as farmers' willingness to plant second-generation feedstocks, the yields of second generation feedstocks, the marginal costs of producing second generation biofuels, and the emergence of E-85 vehicles. These assumptions will also affect price adjustments in land and fuel markets, and therefore leakage, due to the RFS.

Our central finding is that the expansion of biofuels mandated by the RFS can increase or decrease GHG emissions depending on the policy regime being evaluated. Relative to a baseline that includes the VEETC, the RFS increases emissions by 4.5 tgCO_2e in 2015 with our central parameters.[6] Emissions increase because the intended emissions savings due to the RFS are offset by considerable leakage in land and fuel markets, 80% and 60% of intended emissions savings respectively. In contrast, swapping the pre-existing VEETC with the RFS expands domestic ethanol production while reducing GHG emissions, which indicates that allowing the VEETC to expire in 2011 provided emissions benefits. Emissions fall because swapping the VEETC for the RFS reverses the direction of fuel market leakage, which is sufficient to induce a reduction in total emissions of 2.0 tgCO_2e in 2015 and a cumulative reduction in emissions of 25.5 tgCO_2e between 2012 and 2015. Relative to a baseline in which the VEETC is not in place, the RFS increases emissions because leakage in land and fuel markets again offsets intended emissions savings. This suggests that current proposals for eliminating the RFS for conventional biofuels would reduce emissions by 6.7 tgCO_2e in 2015.

The rest of this paper is organized as follows. Section 2 provides details regarding the policy context of this paper. Section 3 develops an analytical model that decomposes the intended emissions savings and carbon leakage from a marginal change in the RFS. Section 4 presents simulation results, and Section 5 concludes.

2. POLICY DETAILS

Although biofuels in the U.S. are supported by a variety of policies at both the state and federal levels, here we focus on two of the most consequential federal policies: the Renewable Fuel Standard (RFS) for conventional biofuels and the Volumetric Ethanol Excise Tax Credit (VEETC). Details regarding other policies that impact ethanol production in the U.S. are provided in the Appendix.[7]

[5] There is considerable uncertainty with respect to whether second generation biofuels will actually be required at the statutory levels specified in EISA because the EPA can scale down the blend requirements for cellulosic biofuels if there is a lack of cellulosic ethanol production capacity.

[6] That the RFS increases emissions relative to a VEETC baseline is robust to parameter assumptions. Across 81 combinations of parameter assumptions we find that the RFS increases emissions in 2015 in 78% of cases, with the change in emissions ranging from a small decrease of 2.2 tgCO_2e to an increase of 27.8 tgCO_2e.

[7] An appendix that contains supporting text, the mathematical structure of our numerical model, details on data and parameters for calibration, and additional results is available at www.joelrlandry.com.

2.1 Renewable Fuel Standard (RFS)

The RFS was established by the Energy Independence and Security Act of 2007 (EISA) with rule-making authority provided to the EPA (U.S. Congress 2007). The RFS is a set of nested mandates specifying the minimum amount of various classes of biofuels that must be blended into the nation's fuel supply, where biofuels are classified according to the lifecycle GHG emissions savings they achieve relative to a fossil fuel derived alternative (gasoline or diesel). The national RFS targets all biofuels that achieve a reduction of at least 20%.[8] Below the national RFS, the RFS for advanced biofuels targets all biofuels that achieve a savings of at least 50%. Since conventional biofuels such as corn ethanol do not meet this threshold, we define the *RFS for conventional biofuels* as the national RFS less the RFS for advanced biofuels. Within the RFS for advanced biofuels, there are separate standards for "cellulosic biofuel", which targets biofuels that must achieve emissions savings of 60% or more, and "biomass-based diesel" which targets biodiesel that must achieve savings of 50% more.

The RFS for conventional biofuels expands from 15.1 billion liters in 2006 to 56.7 billion liters in 2015, after which it remains constant through 2022. The RFS for conventional biofuels applies only to those biofuels that achieve a 20% or greater lifecycle emissions savings. The EPA (2010a) has determined that domestically produced corn ethanol just meets this requirement, achieving lifecycle savings of 21%. It is widely expected that this mandate will be predominantly filled by corn ethanol, given that it is the most cost competitive biofuel in widespread production in the U.S.

There are legitimate reasons to question whether the volumes originally set for advanced biofuels will be achieved in the short run, including the EPA's statutory authority and past willingness to scale down the cellulosic ethanol mandate, current technical limits on the amount of ethanol that can be blended into fuel (the so-called "blend wall"), and constraints on the expansion of ethanol imports.[9] Given this, as well as the lack of credible data on feedstock production and technological conversion efficiency for advanced biofuels, we do not consider the RFS for advanced biofuels in our analysis. A complete discussion regarding our decision to abstract from the RFS for advanced biofuels is provided in the Appendix.

Recently, a bipartisan effort in the House has proposed the RFS Elimination Act (HR 1461), which would eliminate the corn ethanol requirements of the RFS, lower the Advanced RFS, and prohibit ethanol blends greater than 10%. Similar proposals have been offered in the Senate as amendments to the Farm Bill that is currently under debate.

2.2 Volumetric Ethanol Excise Tax Credit

The VEETC was an excise tax credit (deducted from the federal fuel tax) of $0.12 per liter provided to fuel blenders for each unit of ethanol they added into the fuel supply. The VEETC expired at the end of 2011, nearly half a decade after the RFS was first established. Prior to its expiration, ethanol production had been subsidized since the 1978 Energy Tax Act. The VEETC

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[8] Specifically, only biofuels from new facilities that commenced construction after December 19, 2007 must meet this standard. Production from facilities built prior are grandfathered in under EISA 2007.

[9] EISA 2007 includes a "cellulosic loophole" which effectively allows the EPA to scale down the RFS for cellulosic biofuels if production capacity to meet the mandated quantities does not exist. Using this authority, the EPA has lowered the required volumes of cellulosic biofuels to less than 7% of the level set by EISA 2007 in 2010, 2011 and 2012.

was by far the most significant federal support program for biofuels until the RFS was established. Under a non-binding RFS, the VEETC acted as an implicit agricultural support program; however under a binding RFS, the VEETC provides no additional support beyond that provided by the binding RFS.[10] Consequently, the expiration of the VEETC in 2011 provides a useful frame of reference for understanding whether policymakers intended to replace the VEETC with the RFS, a case we explicitly examine below.

3. ANALYTICAL MODEL

In this section we develop an analytical model that integrates fuel, land and food markets to decompose the overall emissions resulting from the RFS into intended emissions savings and carbon leakage in land and fuel markets.

3.1 Economic Model

3.1.1 General Environment

We develop a static model of two countries, D and W, both open economies. D denotes the United States. W represents the rest of the world, a collection of open economies that trade with the U.S. The countries freely trade agricultural crops and crude oil.[11] All other goods 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 domestically. The U.S. implements the RFS for conventional biofuels. We model explicitly the behavior of the agents in the U.S. economy, and treat adjustments in the rest of the world more simply.[12]

3.1.2 Consumer Demand

The representative household receives utility from blended fuel (F), food (X) and a composite consumption good (C). The representative household is endowed with land ($\bar{A}$) and labor ($\bar{L}$). The household's utility function is represented by:

$$U(F,X,C) \tag{1}$$

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[10] Although the expiration of the VEETC was initially opposed by feedstock and ethanol producer groups, many of these groups eventually acquiesced, largely, it appears, due to the presence of the RFS. According to Matthew A. Hartwig of the Renewable Fuels Association: "We may be the only industry in U.S. history that voluntarily let a subsidy expire. . .The tax incentive is less necessary now than it was just two years ago. . .We don't expect the price of corn to fall or rise just because the tax incentive goes away. We will produce the same amount of ethanol in 2012 as in 2011, or more" (Pear 2012). This statement reflects the logic of a tax credit in the presence of a binding mandate. Since the binding mandate determines the amount of ethanol produced in the economy, and thus the equilibrium price of corn in the economy, the VEETC no longer serves as a support program for corn and ethanol production. We believe that the VEETC would have been renewed had the RFS not been in place given the adeptness of these same groups to retain subsidies for ethanol in some form or other for over thirty years, as well as the continual renewal of the renewable Production Tax Credit (PTC) or "wind tax credit" even in the current legislative climate.

[11] We abstract from the trade of gasoline. Between 2005 and 2009, the US imported less than 3% of total finished gasoline consumed, and exported less than 5% of total gasoline produced (US Energy Information Administration).

[12] When describing the US portion of the model, we omit the subscript D as appropriate for ease of notation.

where $U(\cdot)$ is continuous and quasi-concave, and whose budget constraint is given by:

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

where P_F is the price of blended fuel and P_X is the price of food and the wage rate is normalized to unity. $\pi_{\bar{A}}$ is the net return to the land endowment. The household chooses F, X, and C to maximize utility (1) subject to (2). From the resulting first-order conditions we obtain the uncompensated demand functions for blended fuel, food and the composite good are given by:

$$F(P_F,P_X,\pi_{\bar{A}}) \quad X(P_F,P_X,\pi_{\bar{A}}) \quad C(P_F,P_X,\pi_{\bar{A}}). \tag{3}$$

3.1.3 Fuel Production

Blended fuel is produced from gasoline (G) and ethanol (E) with a constant returns to scale production function given by:[13]

$$F = F(G,E). \tag{4}$$

The RFS is modeled as a share mandate for ethanol in the production of blended fuel:[14]

$$E \geq \theta F \tag{5}$$

where θ is the mandated share of ethanol per unit of blended fuel, such that the RFS mandated quantities are achieved.[15]

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[13] Here we present a general formulation for the production of blended fuel. In the simulation model below, we assume that gasoline and ethanol are energy equivalent perfect substitutes. This appears to be the most common specification used (see de Gorter and Just (2009)). We believe this is an appropriate representation because consumers, when they purchase blended fuel at the pump, are largely unaware of the share of ethanol in the fuel they are purchasing. Consumers are, however, sensitive to the fuel economy of the blended fuel they purchase with respect to various retailers, which sell different (unlabeled) ethanol blends. Others authors, however, have somewhat different representations, including Vedenov and Wetzstein (2008) who assume perfect complements, and Ando et al. (2010) who consider a flexible constant elasticity of substitution (CES) specification. With respect to the latter, input-substitution is very sensitive to the share parameter in the CES function, which is calibrated to base year data. Since the share of ethanol in blended fuel has expanded exponentially over the last decade, this is very restrictive when compared to the perfect substitute production function, in which the share of ethanol in blended fuel in the absence of the RFS is solved for endogenously without regard to the calibration year share of ethanol in blended fuel.

[14] We note that EISA established a trading program to ease compliance with the RFS, whereby each unit of biofuel produced is assigned a unique Renewable Identification Number (RIN). These RINs can be separated from the biofuel sold, and can thus be traded independently of the biofuel itself. Individual blenders are required to have enough RINs and/or RIN enumerated ethanol blended into their annual production, so that they meet their individual portion of the RFS (their Renewable Volume Obligation). Since we model a nationally representative fuel blender in order to evaluate a federal policy, spatial smoothing using RINs is not an issue. In effect, this assumes that the market for RINs is efficient and that the RIN market closes in each year.

[15] While the RFS itself states the total amount of biofuel 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 requirement (EPA 2010b). A related concern affects the extent to which ethanol as an input in blended fuel is

The fuel blender chooses E and G to minimize production costs:

$$P_G G + (P_E - \tau)E \tag{6}$$

subject to equation (4) and (5) where P_E and P_G, are the prices of corn ethanol and gasoline respectively and τ is the VEETC. The resulting price of blended fuel, is given by:

$$P_F(P_G, P_E - \tau, \theta) \tag{7}$$

and the final input demand functions for gasoline and ethanol are:

$$G = g_F(P_G, P_E - \tau)F(\cdot) \quad E = e_F(P_G, P_E - \tau)F(\cdot) \tag{8}$$

where $g_F(\cdot)$ and $e_F(\cdot)$ are respectively the per unit conditional factor demands for gasoline and ethanol, and $F(\cdot)$ is the uncompensated demand for blended fuel from (3).

Gasoline and ethanol are produced by perfectly competitive firms with constant returns to scale production technology; gasoline is produced from crude oil, R_G, and labor, L_G, and ethanol is produced from corn, Y_E, and labor, L_E.[16] The production functions for gasoline and ethanol are given by:[17]

$$G = G(R_G, L_G) \quad E = E(Y_E, L_E). \tag{9}$$

The price of gasoline can be written as a function of the price of crude oil, $P_G(P_R)$, and the price of ethanol can be written as a function of the price of corn, $P_E(P_Y)$. Finally the conditional factor demand functions are given by:

$$\begin{array}{ll} Y_E(P_Y, E(\cdot)) & L_E(P_Y, E(\cdot)) \\ R_G(P_R, G(\cdot)) & L_G(P_R, G(\cdot)) \end{array} \tag{10}$$

where $E(\cdot)$ and $G(\cdot)$ are from (8).

3.1.4 Agricultural Production

The representative household maximizes the net returns to its land endowment by allocating land to the production of crops, or setting land aside in the Conservation Reserve Program

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restricted due to technical limitations that are largely under the regulatory purview of the EPA. This so-called ‘blend-wall’ currently restricts the amount of ethanol that can be mixed into blended fuel to be 10% or less. Since our analysis is of the RFS for conventional biofuels through 2015, our model predicts that we just remain under this blend wall, and consequently this is not a concern for our analysis.

[16] Here Y_E is net of co-products, which can be used in livestock rations. In the simulation model, co-products are produced jointly with ethanol and substitute for corn and soybeans in the production of food. See the Appendix for additional details.

[17] While we assume a flexible constant elasticity of substitution functional form to characterize gasoline production, consistent with literature estimates we use an elasticity of substitution that effectively implies a perfectly complementary relationship between labor and crude oil.

(CRP), for which it receives an annual rental payment.[18] Cropland can be allocated to corn production, Y, which can be used to produce food or ethanol, and other crops, Z which are used exclusively for food production.[19] Land enrolled in the CRP is indexed by N.[20]

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

$$\begin{aligned} \pi_{\bar{A}}(P_Y,P_Z,\bar{A}) = \max_{A_i} & \sum_i (P_i y_i(A_i) - l_i)A_i \\ & \text{subject to:} \\ & \sum_i A_i \leq \bar{A} \end{aligned} \tag{11}$$

where P_Y and P_Z are world crop prices, A_i is the quantity of land allocated to land use i and l_i is the amount of labor required per unit land to produce crop i. The functions $y_Y(A_Y)$ and $y_Z(A_Z)$ represent the yields of corn and other crops respectively. The function $y_N(A_N)$ is treated as the per unit land CRP rental payment in dollars, so P_N is set to one. $y_i(A_i)$ are assumed to be monotonically decreasing and concave to reflect decreasing returns to expanded agricultural production and decreasing rental payments for land held in CRP.

In practice, a portion of total CRP acreage comes up for annual renewal as contracts expire, and land that is not up for renewal may also be converted but at the cost of a sizeable penalty which must be paid by the landowner.[21] The changes in CRP predicted by our model are meant to reflect

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[18] The CRP is a government funded program, administered by the USDA, which allows farmers to voluntarily take historical cropland out of agricultural production in exchange for an annual rental payment. There are four major CRP programs, with varying contract lengths, payment rates and enrollment qualifications. 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. 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 we are referring only to the sum of these two sub-categories. Of these two categories, general sign-up provides the bulk of our measure of CRP, constituting on average 92% of our CRP measure between 2003 and 2010.

[19] In our simulation model, we disaggregate Z further and consider soybeans, hay, wheat and cotton.

[20] We abstract from other domestic land uses, such as pastureland, forest land and rangeland. According to the 2007 Natural Resources Inventory, between 2002 and 2007, the transition of land between cropland, forestry and range was small relative to the transition of land between pasture and cropland (U.S. Department of Agriculture 2009). 2002 rangeland and forestland constituted 0.2% of 2007 cropland, which is well within the margin of error reported for 2007 cropland (+/- 0.75%). In contrast, 2002 pastureland accounts for 0.8% of 2007 cropland. On net, these small values reflect the fact that much of what constitutes rangeland, forest land, and pastureland is of considerably lower quality than cropland and/or has a high cost of conversion. To account for pasture, we include in our estimate of cropland, land used to produce continuous hay as reported by the USDA. We think that this is the component of pastureland most likely to be brought into agricultural production since it reflects cultivable pastureland.

[21] CRP contracts have an initial length of 10 to 15 years, but can be extended later for shorter periods. We do not model these contracts explicitly. In addition, we do not explicitly model the environmental benefits of land held in CRP as a requisite for entry into the program. Consequently, cropland exiting the program is likely to be of a lower-quality than cropland remaining in the program, suggesting that any expansion in cropland resulting in reductions in land held in CRP will have marginally lower yields. To implicitly capture this issue, in our specification of the land-allocation problem (see Appendix), we allow yields for each crop considered and rental payments for land held in CRP to be declining in new acreage added. Finally, since we do not track land parcels, we choose emissions coefficients for the conversion of CRP that reflect that land in set aside from cropland may be of lower quality or have a limited soil carbon stock (see the discussion regarding emissions factors in Appendix).

expiring contracts, and for a given year are below the average amount of CRP land that is up for annual renewal.[22] We assume that CRP contracts are never broken, and therefore abstract from this mechanism of CRP conversion.

The first-order conditions of (11) provide the crop supply functions, as well as the optimal allocation of land to the CRP:

$$\begin{aligned} Y(P_Y,P_Z,\bar{A}) &= y_Y(A_Y(P_Y,P_Z,\bar{A}))A_Y(P_Y,P_Z,\bar{A}), \\ Z(P_Y,P_Z,\bar{A}) &= y_Z(A_Z(P_Y,P_Z,\bar{A}))A_Z(P_Y,P_Z,\bar{A}), \\ & A_N(P_Y,P_Z,\bar{A}). \end{aligned} \tag{12}$$

3.1.5 Food Production

Food is produced from corn and other crops by competitive firms with constant returns to scale technology:[23]

$$X = X(Y_X,Z_X,L_X) \tag{13}$$

where Y_X, Z_X and L_X are the quantities of corn, other crops and labor used in food production respectively. Incorporating food production in the model allows us to explicitly capture the trade-off between demand for crops for food production, and demand for crops for ethanol production. The food producer chooses Y_X, Z_X, and L_X to minimize production costs $P_Y Y_X + P_Z Z_X + L_X$ given the food production technology and taking prices as given. Given the demand for food from (3), the conditional factor demands for corn and other crops are:

$$Y_X(P_Y,P_Z,X(\cdot)) \quad Z_X(P_Y,P_Z,X(\cdot)) \tag{14}$$

and $P_X(P_Y,P_Z)$ is the price of food.

3.1.6 Crop Export Demand

The rest of the world responds to the RFS only through price channels. We consider a simplified model of crop exports and specify the rest of world excess demand for U.S. crop exports:

$$Y_{X,W} = Y_{X,W}(P_Y,P_Z) \quad Z_{X,W} = Z_{X,W}(P_Y,P_Z). \tag{15}$$

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[22] Given the frequency of past general sign-ups and renewals, on average approximately 1.3 million general sign-up hectares will come up for renewal for each year between 2010 and 2015 (U.S. Department of Agriculture 2007). We calibrate the supply of CRP land to reflect the annual flow of CRP land that comes up for renewal in a given year. We never find more than a third of these 1.3 million hectares being converted in a given year. In Appendix Section VII we validate these changes in CRP to changes observed in recent years. In general, the changes predicted by our model are consistent with those observed in recent years.

[23] We treat food as a composite of all final food products. As such our food sector encompasses intermediate sectors such as livestock production. We note that while livestock production is emissions intensive, we do not explicitly model the livestock sector because the RFS is expected to have a limited impact on emissions from livestock production (EPA 2010a).

To account for land use change in the rest of the world, we assume that each unit of crop exports displaced results in a constant quantity of rest of world non-agricultural land (which we treat as a composite of land uses including forest, grassland, shrubland and savanna among others) being converted to cropland.[24]

3.1.7 Crude Oil Supply

The rest of world excess supply curve for crude oil is given by:[25]

$$R = R(P_R). \tag{16}$$

We let $R_W(P_R)$ denote the rest of world demand for crude oil that underlies the excess supply of crude oil.

3.1.8 Equilibrium

An equilibrium consists of a price vector, P_Y, P_Z, P_R, such that the world markets for agricultural crops (Y and Z) and crude oil:

$$\begin{aligned} Y_D &= Y_{X,D} + Y_{E,D} + Y_{X,W} \\ Z_D &= Z_{X,D} + Z_{X,W} \\ R_W &= R_{G,D} \end{aligned} \tag{17}$$

and the labor market in the U.S. clears and the government budget is balanced.[26]

3.2 Greenhouse Gas Emissions

We link the economic model above with a disaggregated model of greenhouse gas emissions (GHG) given by:

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

---

[24] We take a reduced form approach here in order to provide a transparent accounting of emissions arising from rest of world land use change. Given the uncertainty regarding the mechanisms of land use adjustment (EPA 2010a; Searchinger et al. 2008; Hertel, Tyner, and Birur 2010) and the elasticity of the aggregate supply of cropland (Barr et al. 2011), we vary the rate at which reduced crop exports are translated to rest of world land use change in sensitivity analysis. Further, we vary the emissions generated by land use change in the rest of the world, which implicitly reflects the makeup of land converted to cropland in the rest of the world. This allows us to account for the possibility that land converted to cropland is predominantly converted from uses with small or large carbon stocks, such as pasture or forest respectively.

[25] Studies suggest that OPEC operates as an imperfect cartel (Griffin and Xiong 1997). Although we do not explicitly model market power in this market, in the sensitivity analysis below, we do examine the implications of price responsiveness on total emissions and leakage by varying the elasticity of excess supply.

[26] Although not discussed above, the government finances the VEETC, CRP payments, and a lump sum transfer to the representative agent from a non-distortionary labor tax. The lump-sum transfer is also searched for under the identifying equation that the government's budget is balanced.

where ϕ_i are GHG emissions released per unit of good or activity i (where i spans the economic sectors previously enumerated), and all quantities and emissions factors are specific to country D unless otherwise indexed.[27]

3.2.1 Intended Emissions Savings of the RFS

Given that the RFS has adopted lifecycle emissions savings as the primary metric for assessing the emissions impacts of biofuels, we use this metric to calculate the *intended emissions savings* of the RFS.[28] Emissions in excess of those intended correspond to emissions leakage. Standard lifecycle metrics of corn ethanol rely on two critical simplifying assumptions. First, it is assumed that for every additional unit of ethanol produced, a constant quantity of land, $\tilde{A}_Y$, is brought into cultivation to grow the corn needed to produce that unit of ethanol.[29] Second, each unit of ethanol is assumed to displace an energy equivalent unit of gasoline. We demonstrate in the simulation results that these two assumptions will not hold if the RFS has an impact on equilibrium prices. As documented in Bento and Klotz (2014) lifecycle metrics can fail to account for the full emissions implications of the RFS and are likely to be a poor criteria on which to evaluate the emissions impacts of alternative biofuel policy options. With intended emissions savings defined in this manner, leakage measures the impact of the RFS on emissions net of increased emissions from the expanded production of ethanol and corn calculated using lifecycle methods and emissions reductions from a one-to-one displacement of gasoline with ethanol.

3.3 The Effects of the RFS on Greenhouse Gas Emissions

Consider a marginal increase in the RFS. The resulting impact on GHG emissions can be decomposed as (See Appendix for full derivation):

$$
\begin{aligned}
\frac{dGHG}{d\theta} &= \underbrace{(\phi_E + \phi_Y\tilde{A}_Y - \phi_G)\frac{dE}{d\theta}}_{I} \\
&+ \underbrace{\underbrace{\phi_Y\left(\frac{dA_Y}{d\theta} - \tilde{A}_Y\frac{dE}{d\theta}\right)}_{L^Y} + \underbrace{\phi_Z\frac{dA_Z}{d\theta}}_{L^Z} + \underbrace{\phi_{N,D}\frac{dA_{N,D}}{d\theta}}_{L^N}}_{L^{DA}} \\
&+ \underbrace{\phi_{N,W}\frac{dA_{N,W}}{d\theta}}_{L^{WA}} + \underbrace{\phi_G\frac{dF}{d\theta}}_{L^{DF}} + \underbrace{\phi_R\frac{dR_W}{d\theta}}_{L^{WF}}.
\end{aligned}
\tag{19}
$$

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[27] While the marginal emissions coefficient for gasoline is inclusive of the emissions from both gasoline consumption and production, we consider only the emissions from ethanol production because the carbon stored in ethanol and released during ethanol combustion, is absorbed from the atmosphere during the growth of corn (IPCC 2007).

[28] While EISA established mandates for fuels based upon their meeting a GHG intensity threshold, analyses at the time of passage regularly inferred emissions savings given the expected amount of ethanol added by the policy and the expected GHG intensity of the fuels. Our characterization of intended emissions savings thus reflects the understanding of the EPA at the time EISA was passed. For example, the EPA's Regulatory Impact Analysis of RFS1, which was conducted just prior to EISA's passage in 2007 (EPA 2007) assumes a GHG intensity for corn ethanol that ignored fuel market and world land market leakage and assumed that emissions from domestic land market adjustments were very small. We note that our characterization of intended emissions savings has no bearing on the net emissions results of our analysis.

[29] Letting $\lambda_{E,Y}$ represent the per-unit factor demand for corn for ethanol production, then $\tilde{A}_Y = \lambda_{(E,Y)}/y_Y$, where y_Y is the yield for corn, which is assumed to be independent of land already devoted to corn.

I, the first term on the right-hand side of equation (19), represents the *intended emissions savings* of the RFS. The intended emissions savings equals the (per-unit) lifecycle emissions savings of ethanol relative to gasoline, which is the term $(\phi_E + \phi_Y\tilde{A}_Y - \phi_G)$, multiplied by the change in ethanol due to the RFS. The lifecycle emissions savings of ethanol is the sum of the per unit emissions of ethanol production and the emissions from the corn required to produce a unit of ethanol, net of the lifecycle emissions of an energy equivalent unit of gasoline. I is linear in the amount of ethanol added by the RFS, $\frac{dE}{d\theta}$, and therefore fails to completely capture the impact of the RFS on emissions that stem from price adjustments. We call these price adjustment driven effects leakage.

The remaining terms on the right-hand side of equation (19) decompose the sources of carbon leakage in land and fuel markets. The first term, L^{DA} denotes *leakage from the domestic land market* and arises from three sources. The first two sources, $L^Y + L^Z$, comprise leakage from the intensive margin of land use. L^Y, isolates leakage from changes in food and export demand for corn. L^Z isolates leakage from changes in food and export demand for other crops. L^Y is equal to the total change in emissions from corn production, less the change in emissions from corn production that are attributed to expanded ethanol production in the calculation of I.

Both L^Y and L^Z are negative. The RFS will drive up all crop prices, but more so the price of corn, leading to two effects: a reallocation of cropland, and a reduction in the amount of crops demanded by the domestic food producer and rest of world crop exporters. As a result, the *actual* expansion of land allocated to corn production at the expense of other crops—adjustments along the intensive margin—are less than what are predicted by lifecycle methods, since price adjustments are ignored. Therefore, leakage from the intensive margin of land use is negative, implying emissions reductions that are beyond those accounted for in I. Negative leakage from the intensive margin of land use does not mean that emissions from domestic agriculture decline. Rather, L^Y and L^Z are negative because emissions from corn production are over accounted by the lifecycle methods that determine intended emissions savings.[30]

The third source of leakage from the domestic land market, L^N, represents leakage from the extensive margin of land use. L^N is equal to the lifecycle emissions benefits of CRP land multiplied by the change in land allocated to the CRP. Unlike leakage from the intensive margin, L^N is positive. As the RFS increases the prices of corn and other crops, the net returns to cropland also increase. In response, some land held in CRP is converted to cropland. Given that land held in CRP provides emissions benefits, this adjustment causes emissions to increase, a source of positive leakage. *A priori*, it is not possible to infer whether leakage from the domestic land market will be positive or negative. The direction depends on the magnitude of the negative leakage from the intensive margin relative to the positive leakage from the extensive margin.

L^{WA} denotes *leakage from the world land market* and equals the emissions benefits from non-agricultural land in the rest of the world, multiplied by the change in world land allocated to non-agricultural uses.[31] In response to the RFS, U.S. crop exports will fall. In order to replace these

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[30] As discussed in the results section, we find that the RFS will cause total emissions from domestic agriculture to increase.

[31] We note that the lifecycle assessment conducted by the EPA to categorize biofuels for the RFS incorporates both domestic and international land use adjustments (EPA 2010a). For comparison to EPA assessment, L^{DA} and L^{WA} would be included in the estimate of intended emissions savings. We maintain our simple definition of I because it allows us to cleanly illustrate the mechanisms of each source of land use leakage. Moreover, it is not clear *a priori* whether the joint determination of fuel and land market equilibria will affect L^{DA} and L^{WA}.

lost exports, the rest of the world will expand cropland at the expense of non-agricultural land, leading to positive leakage as the climate benefits of non-agricultural land are lost.

Together, L^{DA} and L^{WA} make up total *land market leakage*. Whether land market leakage is positive or negative cannot be directly inferred from the analytical model.

L^{DF} denotes *leakage from the domestic fuel market* and equals the lifecycle emissions of gasoline multiplied by the change in blended fuel due to the RFS. Depending on the degree to which prices of ethanol and gasoline change in response to the RFS, as well as the share of ethanol in blended fuel, the RFS could impact the price and consumption of blended fuel (de Gorter and Just 2009). However, the direction of the change in blended fuel, which determines whether L^{DF} will be positive or negative, is ambiguous.[32] A binding RFS will increase demand for ethanol, and therefore corn, causing the price of ethanol to increase relative to a counterfactual equilibrium without the RFS. In turn, the RFS will reduce the demand for gasoline which will lead to a decrease in the price of gasoline.

L^{WF} denotes *leakage from the world crude oil market* and equals the emissions from crude oil consumption multiplied by the change in rest of world crude oil demand due to the RFS. This term unambiguously is positive because the RFS reduces U.S. demand for gasoline and therefore crude oil. This depresses the world price of crude oil and leads to increased world consumption of crude oil, corresponding to positive leakage.

The sum of L^{DF} and L^{WF} make up total *fuel market leakage*. Fuel market leakage can be positive even if global fuel use declines.[33] Intended emissions savings include a measure of the emissions reduction from displaced gasoline, based on the assumption that each unit of ethanol added by the RFS displaces an energy equivalent unit of gasoline, and ignores any change in rest of world crude oil use. Positive fuel market leakage signifies that the reduction in gasoline assumed to occur when calculating intended emissions savings over predicted the total reduction in global fuel use. Thus, fuel market leakage will be positive unless domestic fuel market leakage is sufficiently negative to offset positive leakage in the world crude oil market.

4. NUMERICAL RESULTS

We supplement the analytical model developed above with a numerical model that we use to quantify each of the terms in equation (19) for the years 2009–2015. Our central analysis compares the RFS to a baseline in which the VEETC is in place through 2015. This implicitly assumes that, in the absence of the RFS, policymakers would have otherwise continued to support biofuels through the VEETC which is fully consistent with the U.S.'s long history of biofuel support through subsidization. This baseline is also consistent with our characterization of intended emissions savings, as the reduction in emissions anticipated by a representative policymaker at the time that the RFS was enacted, since the VEETC was in place at this time.

Relative to a baseline that includes the VEETC, our central analysis considers two policy regimes. Our first policy regime imposes the RFS, while retaining the VEETC already in place through 2015. This simulation isolates just the contribution of the RFS relative to a pre-existing

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[32] The blended fuel sector is a key feature of our framework because, unlike previous studies of greenhouse gas emissions from biofuels such as (EPA 2010a), we do not restrict the rate at which ethanol displaces gasoline to be one-to-one.

[33] In our model, total world consumption of petroleum based fuels includes domestic gasoline and ROW crude oil. In our simulations we find that total world consumption of petroleum based fuels declines, but that leakage from fuel markets can be positive or negative.

policy regime that includes the VEETC. With the RFS in place, however, it is less clear whether policymakers intended to keep both the RFS and VEETC in perpetuity, and as noted earlier the VEETC was allowed to expire at the end of 2011. Therefore, relative to the same baseline that includes the VEETC, we consider a second policy regime in which the RFS is imposed but the VEETC is removed for all years through 2015. This simulation isolates the effects of swapping the VEETC with the RFS. We keep the VEETC in the baseline because in the absence of the RFS it is likely that policymakers would have continued to support ethanol production through the VEETC. While these two analyses aim to capture recent changes in biofuel regimes, our simulations compare each regime for all years through 2015. Thus, the latter policy regime compares a baseline with the VEETC to a counterfactual of just the RFS for all years, not just from 2012 onward following the expiration of the VEETC at the end of 2011.

In addition to our central analysis, we evaluate the RFS relative to a baseline in which the VEETC is absent. This isolates the contribution of the RFS under the assumption that the VEETC had never been in place. It also allows us to evaluate the emissions implications of recent proposals to eliminate the RFS for conventional biofuels, given that the VEETC has expired and would not be reintroduced. We note that the fundamental economic intuition that explains this case is very similar to our central assessment of the RFS when the VEETC is renewed. For succinctness, we report the change in ethanol added by the RFS for this case in Table 2 and the total change in emissions in Table 8, but omit the intermediate tables that decompose the sources of leakage.[34] We also use this case to discuss the implications of our analysis to other studies that have assumed constant land market leakage.

A full discussion of the functional forms used in our numerical model, the data sources used to calibrate the model parameters and emissions factors, how the model parameters dynamically evolve over time, and the justification of central, upper and lower (used in sensitivity analysis) parameter values is left for the Appendix. In Table 1 we present several of the key elasticities and emissions factors used in the numerical model. These are consistent with literature values.

4.1 Model Validation

While we calibrate the model using 2003 data, we allow the model to run for each year between 2004 and 2009. This provides five years of model predictions that we can be compared against observed data in order to validate the baseline predicted by our model. Over this period either the RFS was not in place (pre-2006) or resulted in ethanol volumes significantly above mandated levels (post-2006), and thus was not binding. The full results of this analysis are presented in Appendix Table A.8. In general, our model performs quite well especially in light of the highly variable crop and crude oil prices over this period. On average between 2004 and 2009, we slightly underpredict observed harvested acreage for corn, soybeans, and CRP acreage by 1.78%, 0.56%, and 1.50%, respectively, while overpredicting wheat by 1.08%. Our predicted ethanol baseline overpredicts by 8.62% on average.

4.2 Impact of RFS on Ethanol and Intended Emissions Savings

The first row of Table 2 displays the baseline estimates of ethanol quantities with the VEETC in place. Rising crude oil prices and improvements in crop yields drive up the amount of

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[34] Appendix Table A.14 provides intermediate results for the analysis of the RFS relative to a baseline without the VEETC.

Table 1: Key Central Elasticity Values and Emissions Factors

Key Elasticities	
Blended Fuel Demand	−0.34
Food Demand	−0.12
Corn Supply (area)	0.29
Other Crops Supply wrt to Corn Price	−0.12
CRP wrt to Net Returns to Cropland	−0.07
Corn Export Demand	−0.65
Other Crops Export Demand	−0.59
Crude Oil Excess Supply	0.50
Emission Factors	
Ethanol, ϕ_E	0.6 kgCO$_2$e/liter
Gasoline, ϕ_G	3.0 kgCO$_2$e/liter
Crude Oil, ϕ_R	2.6 kgCO$_2$e/liter
Corn, ϕ_Y	3.2 mgCO$_2$e/ha
Other Crops, ϕ_Z	0.9 mgCO$_2$e/ha
CRP, $\phi_{N,D}$	2.3 mgCO$_2$e/ha
ROW, $\phi_{N,W}$	8.0 mgCO$_2$e/ha

Notes: Here the emissions factor for other crops represent the average of soybean, wheat, hay and cotton weighted by the 2003 land allocation. In the simulation model, each of these crops is considered separately. Likewise, the emissions factor for crude oil is the average emissions from gasoline and distillates used outside the US, weighted by 2003 quantities of these products. Elasticities, except where otherwise noted are own-price elasticities. With the exception of ethanol which includes only the emissions from production and non-CO$_2$ emissions from combustion, and crude oil, the emissions factors represent lifecycle emissions for an activity or good.

ethanol in the economy from 40.1 billion liters in 2009 to 45.4 billion liters in 2015. Our baseline is approximately 10% higher than the baseline used by the U.S. EPA (2010a) and roughly 6% lower than the baseline implied by the USDA's 2008 Long Term Agricultural Projections.[35]

The second row of Table 2 presents the amount of ethanol added to the economy as a result of the RFS relative to the baseline with the VEETC in place. The RFS does not bind in 2009, hence no ethanol is added to the economy as a result of the RFS. For this reason, in the tables that follow we do not report results for 2009. The RFS binds in the remaining years, forcing additional ethanol in the economy. In 2012, the RFS increases ethanol consumption by 6.1 billion liters. By 2015, the amount of ethanol added as a result of the RFS nearly doubles, reaching 11.4 billion liters. When the RFS is swapped for the VEETC (row three), the amount of ethanol added by the RFS is roughly the same since the RFS binds.

The fourth row of Table 2 reports the per liter lifecycle emissions savings of ethanol relative to gasoline, the term $\phi_E + \phi_Y\tilde{A}_Y - \phi_G$, in equation (19). In 2009, we find that the lifecycle emissions savings of ethanol relative to gasoline is 0.8 kgCO$_2$e/liter. This is consistent with other estimates (Farrell et al. 2006; Liska et al. 2009).[36]

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[35] See Appendix section VII and Appendix Table A.9.

[36] Using 2009 values for corn yields and corn-to-ethanol conversion efficiency, the amount of land required for ethanol production, $\tilde{A}_Y$, are 0.19 ha/1000 liters and therefore the lifecycle emissions of corn ethanol, $\phi_E + \phi_Y\tilde{A}_Y$, are 1.17 kgCO$_2$e/liter. Relative to gasoline, ethanol achieves 40% emissions savings after adjusting for the relative energy content of the two fuels. Over time, the lifecycle emissions savings of ethanol increases due to exogenous improvements in corn yields and ethanol production efficiency that are imposed between years of the simulation.

Table 2: Ethanol Added and Intended Emissions Savings due to RFS

	2009	2012	2015
Ethanol Baseline, with VEETC (billion liters)	40.1	43.9	45.4
Change in Ethanol Due to RFS (VEETC Renewed)	0.0	6.1	11.4
Change in Ethanol Due to RFS (VEETC Swapped)	0.0	5.8	11.1
Lifecycle Emissions Savings of Ethanol (kgCO_2e/liter)	0.80	0.82	0.84
Intended Emissions Savings, *I* (tgCO_2e)			
Savings Due to RFS (VEETC Renewed)	0.0	5.1	9.7
Savings Due to RFS (VEETC Swapped)	0.0	4.8	9.5
Ethanol Baseline, no VEETC (billion liters)	21.2	24.5	31.2
Change in Ethanol due to RFS	18.8	25.8	25.8
Lifecycle Emissions Savings of Ethanol (kgCO_2e/liter)	0.83	0.86	0.87
Intended Emissions Savings, *I* (tgCO_2e)	15.7	22.1	22.4

Notes: Baseline reported is inclusive of the VEETC.

The next row reports the *intended emissions savings* of the RFS, the term *I* from equation (19), which is the product of the per liter lifecycle emissions savings and the amount of ethanol added by the RFS. In 2012, intended emissions savings of the RFS are 5.1 tgCO_2e. Over time, *I* increases in proportion to the amount of ethanol added by the RFS. By 2015, following the approximate doubling in the amount of ethanol added by the RFS, *I* nearly doubles to 9.7 tgCO_2e. When the RFS binds, the VEETC has no impact on the amount of ethanol in the economy. When the RFS binds, the VEETC has no impact on the amount of ethanol in the economy. As a result, the intended emissions savings of the RFS are unaffected by the renewal or expiration of the VEETC. Below, we compare each leakage source to intended emissions savings by reporting leakage as a percentage of intended emissions savings. While our leakage results may, at first, appear implausible, we note that this is because the intended emissions savings of the RFS are modest because in this calculation the lifecycle estimates of emissions from expanded ethanol and corn production offset a majority of the emissions savings from displaced gasoline.[37]

The second panel in Table 2 displays the ethanol added and intended emissions savings due to the RFS relative to a baseline without the VEETC in place. As shown in the first row, baseline ethanol quantities increase from 21.2 billion liters of in 2009 to 31.2 billion liters in 2015 when the VEETC is not in place. Since the baseline without the VEETC is considerably lower than our central baseline that includes the VEETC, the amount of ethanol added by the RFS in this case is larger, with the RFS contributing 25.1 billion liters of ethanol to the economy in 2012 and 25.8 billion liters in 2015 (row 2). As a result, the main mechanism that our decision to include the VEETC in the baseline will have on our estimates of emissions due to the RFS will be through the amount of ethanol that the RFS adds to the economy. However, the fundamental economic intuition

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[37] To aid in the interpretation of our results, we note that corn (3.2 mgCO_2e/ha) is roughly three times as emissions intensive as the average of the other crops (0.9 mgCO_2e/ha), and the conversion of land to agriculture in the rest of the world (8 mgCO_2e/ha) is nearly four times more emissions intensive than the conversion of CRP to cropland (2.3 mgCO_2e/ha).

Table 3: Impact of RFS on Domestic and International Land Use

	2012	2015
RFS (VEETC Renewed)		
Domestic Corn Baseline (million ha)	33.9	33.4
Additional Corn Required	1.1	2.0
Change in Domestic Corn	1.0	2.0
From Other Crops	−0.8	−1.4
From Land Held in CRP	−0.3	−0.5
Change in World Non-Agricultural Land	−0.5	−1.1
RFS (VEETC Swapped)		
Domestic Corn Baseline (million ha)	33.9	33.3
Additional Corn Required	1.1	1.9
Change in Domestic Corn	1.0	1.9
From Other Crops	−0.8	−1.4
From Land Held in CRP	−0.3	−0.5
Change in World Non-Agricultural Land	−0.5	−1.1

Notes: Baselines reported are inclusive of the VEETC. “Additional Corn Required” is the amount of land needed to produce the ethanol added by the RFS. “Other crops” includes soybeans, wheat, hay and cotton.

that explains this case is very similar to our central assessment of the RFS when the VEETC is renewed.

4.3 Impacts on Land Use

Table 3 summarizes the impact of the RFS on domestic and international land use. The first row in the top panel displays the amount of land allocated to corn production in the baseline. In 2012, we predict that 33.9 million hectares of land will be allocated to corn production. The next row reports the amount of additional land allocated to corn production needed to fulfill the mandated expansion in ethanol, 1.1 million hectares in 2012, under the assumptions of LCA (this is $\tilde{A}_Y \frac{dE}{d\theta}$ in equation (19)). However, as the RFS drives crop prices up, the demand for crops by the food sector and for exports declines, alleviating part of the initial pressure to expand corn production in response to the RFS. Thus, the *actual* change in the amount of land actually allocated to corn production, reported in row three, is only 1.0 million hectares. Similarly, the demand for other crops by the food sector and crop exporters also contracts, leading to a 0.8 million hectare reduction in the amount of land allocated to the production of other crops (row four).

As crop prices rise, the net returns to cropland increase relative to the rental payment received for holding land in CRP, causing an adjustment along the extensive margin. As provided in the fifth row, this adjustment corresponds to 0.3 million hectares of CRP land returning to cropland. The final row reports the impact of the RFS on rest of world land allocated to purposes other than agricultural production. To replace crops previously exported from the U.S., rest of world non-agricultural land (cropland) declines (expands) by 0.5 million hectares in 2012.

Corresponding to the approximate doubling in the amount of ethanol added between 2012 and 2015, land use adjustments also approximately double.[38] For example, the additional land

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[38] This latter result is largely due to our assumption of constant crop acreage elasticities over time.

Table 4: Land Market Leakage from RFS

	2012	2015
RFS (VEETC Renewed)		
Intended Emissions Savings, I (tgCO$_2$e)	5.0	9.7
Total Land Market Leakage	70.2%	84.4%
Leakage From the Domestic Land Market, L^{DA}	−9.4%	−8.4%
From Changes in Food and Export Demand, L^{Y}	−7.1%	−6.5%
From the Intensive Margin of Land Use, L^{Z}	−14.6%	−14.4%
From the Extensive Margin of Land Use, L^{N}	12.3%	12.5%
Leakage From the World Land Market, L^{WA}	79.6%	92.8%
Change in Emissions, Corn in Intended (tgCO$_2$e)	3.5	6.3
Change in Emissions Domestic Land Market (tgCO$_2$e)	3.0	5.5
RFS (VEETC Swapped)		
Intended Emissions Savings, I (tgCO$_2$e)	4.8	9.5
Total Land Market Leakage	71.6%	85.6%
Leakage From the Domestic Land Market, L^{DA}	−9.2%	−8.3%
From Changes in Food and Export Demand, L^{Y}	−6.9%	−6.4%
From the Intensive Margin of Land Use, L^{Z}	−14.7%	−14.4%
From the Extensive Margin of Land Use, L^{N}	12.4%	12.5%
Leakage From the World Land Market, L^{WA}	80.8%	93.9%
Change in Emissions, Corn in Intended (tgCO$_2$e)	3.3	6.1
Change in Emissions Domestic Land Market (tgCO$_2$e)	2.9	5.3

Notes: All leakage values are reported as a percentage of intended emissions savings, I. Emissions from the domestic land market includes emissions from crop production and the domestic conversion of land to cropland.

allocated to corn production increases from 1.0 million hectares in 2012, to 2.0 million hectares in 2015.

The effects of swapping the RFS for the VEETC are displayed in the second panel of Table 3. As the binding RFS determines the amount of ethanol added to the economy, swapping the VEETC for the RFS has no additional impact on land use or crop prices.[39]

4.3.1 Land Market Leakage

Table 4 reports land market leakage as a percentage of intended emissions savings. As displayed in the second row, total land market leakage is positive and large in magnitude. *Leakage from the world land market* (presented in row eight) represents the bulk of this effect. Despite being negative, *leakage from the domestic land market* (row three) is negligible in magnitude relative to leakage from the world land market. In 2012, total land market leakage offsets 70.2% of the 5.0 tgCO$_2$e intended emissions savings, with negative leakage from the domestic land market of 9.4%, only partially offsetting the overwhelmingly positive leakage from the world land market of 79.6%. L^{WA} dominates total land market leakage because the emissions released from bringing one hectare of land into crop production in the rest of the world is emissions intensive (see Table 1). While highly uncertain, it is the the potentially large magnitude of leakage from the world land market

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[39] See Appendix Table A.12.

that caused much of the earlier literature to focus on quantifying this effect (e.g. Searchinger et al. (2008) and Hertel et al. (2010)).

Although net domestic land market leakage is small, examining this magnitude in isolation masks the contradictory changes in the domestic land allocation which yields this result. As reported in rows four through six, L^{DA} is negative because negative leakage arising from adjustments within the intensive margin of -14.6%, more than offsets positive leakage arising from adjustments along the extensive margin of 12.3%.[40] That leakage from the domestic land market is negative does not correspond to a reduction in emissions from domestic agriculture. On the contrary, as displayed in rows 8 and 9 of Table 4, leakage from the domestic land market is negative because the emissions from increased corn production included as intended emissions savings, 3.5 $tgCO_2e$, actually over account for the change in emissions from the domestic land market, 3.0 $tgCO_2e$.

In 2015, total land market leakage is again positive, or 85.3% of intended emissions savings of 9.6 $tgCO_2e$, because positive leakage from the world land market continues to wipe out negative leakage from the domestic land market.

Consistent with the findings of Table 3, land market leakage resulting from swapping the RFS for the VEETC is identical to land market leakage resulting from the RFS when the VEETC is renewed.

4.4 Impacts on Fuel Markets

The impact of the RFS on domestic and world fuel markets are displayed in Table 5. We first focus on the impacts on domestic blended fuel consumption, followed with a discussion of the impacts on world crude oil consumption.

The change in blended fuel consumption depends on how the price of blended fuel responds to the RFS, which is reported in row two of Table 5. Whether the price of blended fuel decreases as a result of the RFS depends upon whether the price of ethanol increases sufficiently to offset the fall in the price of gasoline. As a simple rule, given that ethanol remains roughly 10% of a liter of blended fuel both before and after the RFS is introduced, for the price of blended fuel to decrease, the percentage increase in the price of ethanol must be no greater than ten times the percentage decline in the price of gasoline. In 2012, the RFS reduces the price of blended fuel by 0.3% if the VEETC is renewed. This reduction occurs because the increase in the price of ethanol of 10.3% (displayed in row four) is not sufficient to offset the fall in the price of gasoline of 1.3% (row six).

As reported in the eighth row, the fall in the price of blended fuel due to the RFS results in an increase in blended fuel consumption of 0.6 billion liters. In 2015, the price of blended fuel also declines with the RFS, now by 0.4%. The corresponding increase in blended fuel consumption is 1.0 billion liters.

The impact of swapping the RFS for the VEETC on fuel markets is displayed in the lower panel of Table 5. Swapping the RFS for the VEETC has a dramatically different impact on fuel markets than the RFS when the VEETC is renewed. Swapping the VEETC for the RFS results in the same change in the producer price of ethanol as the VEETC renewed case. However, the removal of the subsidy results in a greater increase in the price of ethanol faced by fuel blenders, equal to the amount of the eliminated subsidy. Correspondingly, the price of ethanol increases by 51.7% in

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[40] To the extent that there are shifts away from livestock production, our framework would actually underestimate the potential for negative leakage due to increased crop and food prices.

Table 5: Impact of RFS on Fuel Markets

	2012	2015
RFS (VEETC Renewed)		
Baseline Blended Fuel Price ($/liter)	0.60	0.64
Change in Price of Blended Fuel	−0.3%	−0.4%
Baseline Ethanol Price ($/liter)	0.28	0.31
Change in Price of Ethanol	10.3%	20.5%
Baseline Gasoline Price ($/liter)	0.42	0.46
Change in Price of Gasoline	−1.3%	−2.5%
Baseline Blended Fuel (billion liters)	472.4	472.8
Change in Blended Fuel	0.6	1.0
Baseline Crude Oil Price ($/liter)	0.44	0.50
Change in Crude Oil Price	−1.6%	−3.1%
Baseline World Crude Oil (billion liters)	2,139.0	2,219.7
Change in World Crude Oil	0.7	1.4
RFS (VEETC Swapped)		
Baseline Blended Fuel Price ($/liter)	0.60	0.64
Change in Price of Blended Fuel	1.3%	1.2%
Baseline Ethanol Price ($/liter)	0.28	0.31
Change in Price of Ethanol	51.7%	58.5%
Baseline Gasoline Price ($/liter)	0.42	0.46
Change in Price of Gasoline	−2.0%	−3.3%
Baseline Blended Fuel (billion liters)	472.4	472.9
Change in Blended Fuel	−1.9	−1.7
Baseline Crude Oil Price ($/liter)	0.44	0.50
Change in Crude Oil Price	−2.6%	−4.2%
Baseline World Crude Oil (billion liters)	2,139.0	2,219.7
Change in World Crude Oil	1.1	1.8

Notes: Baselines reported are inclusive of the VEETC. Price of ethanol includes the VEETC and price of blended fuel reported is inclusive of a pre-existing fuel tax of 0.10 $/liter. World crude oil reported here includes only the components of the world crude oil market from which we calculate emissions from: crude oil used to produce gasoline in the rest of the world, and crude oil used to produced distillate fuels in the US and the rest of the world. See discussion in the Appendix.

2012, which is easily more than ten times the fall in the price of gasoline of 2.0%. Swapping the RFS for the VEETC causes the price of blended fuel to increase 1.3% and the consumption of blended fuel to fall by 1.9 billion liters.[41] In 2015, the price of blended fuel increases by 1.2%, which corresponds to a reduction in blended fuel of 1.7 billion liters.

Unlike the price of blended fuel, the RFS unequivocally lowers the world price of crude oil (displayed in the tenth row) regardless as to whether the VEETC is renewed or eliminated. In 2012, the RFS causes the price of crude oil to decline by 1.6% when the VEETC is renewed. In response, rest of world consumption of crude oil increases by 0.7 billion liters (4.4 million barrels). In 2015, when the RFS increases ethanol consumption by roughly 11 billion liters, the reduction

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[41] The price of blended fuel equals the price of ethanol, net of VEETC, weighted by the share of ethanol in each liter of blended fuel plus the price of gasoline weighted by the share of gasoline in each liter of blended fuel (energy-equivalence adjusted). Hence, when the VEETC is present in the baseline but is removed when the RFS is imposed, the change in the price of blended fuel reflects the sum of changes in share weighted input prices, plus an additional VEETC term, which further pushes up the price of blended fuel relative to the VEETC inclusive baseline. See Appendix for further discussion.

Table 6: Fuel Market Leakage from RFS

	2012	2015
RFS (VEETC Renewed)		
Intended Emissions Savings, I ($tgCO_2e$)	5.0	9.7
Total Fuel Market Leakage	61.8%	62.1%
From the Domestic Fuel Market, L^{DF}	26.2%	25.3%
From the World Crude Oil Market, L^{WF}	35.6%	36.7%
Reduction in Gasoline Emissions in Intended ($tgCO_2e$)	12.0	22.6
Reduction in Total Fuel Market Emissions ($tgCO_2e$)	8.9	16.6
RFS (VEETC Swapped)		
Intended Emissions Savings, I ($tgCO_2e$)	4.8	9.5
Total Fuel Market Leakage	−66.5%	−6.8%
From the Domestic Fuel Market, L^{DF}	−127.0%	−57.5%
From the World Crude Oil Market, L^{WF}	60.5%	50.7%
Reduction in Gasoline Emissions in Intended ($tgCO_2e$)	11.5	22.0
Reduction in Total Fuel Market Emissions ($tgCO_2e$)	14.7	22.6

Notes: All leakage values are reported as a percentage of intended emissions savings, I. Total fuel market emissions include emissions from domestic fuel and crude oil in the rest of the world.

in the price of crude oil is 3.1%, and world crude oil consumption increases by 1.4 billion liters (8.8 million barrels).

As illustrated by the lower panel of Table 5, swapping the RFS for the VEETC results in a stronger negative impact on the price of crude oil and therefore causes a larger increase in rest of world crude oil consumption. This larger fall in the price of crude oil corresponds to the additional reduction in blended fuel and gasoline that is induced when the RFS is swapped for the VEETC relative to when the VEETC is renewed. In 2012, swapping the RFS for the VEETC causes the price of crude oil to fall by −2.6% and rest of world crude oil consumption to increase by 1.1 billion liters (7.2 million barrels). In 2015, this policy change causes world crude oil consumption to increase by 1.9 billion liters (11.8 million barrels).

4.4.1 Fuel Market Leakage

Table 6 presents leakage in fuel markets due to the RFS. Total fuel market leakage, reported in the second row, offsets 61.8% of intended emissions savings in 2012. The third and fourth rows decompose total fuel market leakage into *leakage from the domestic fuel market* and *leakage from the world crude oil market*, L^{DF} and L^{WF} from equation (19). Leakage from the domestic fuel market accounts for approximately two-fifths of total fuel market leakage, or 26.2% of intended emissions savings. Leakage from the world crude oil market is slightly larger at 35.6% of intended emissions savings. In 2015, total fuel market leakage increases slightly to 62.1%, of which domestic fuel market leakage continues to contribute approximately two-fifths. Positive leakage in fuel markets does not imply that emissions from global fuel use increase. In 2015, reductions in domestic gasoline emissions used to calculate intended emissions savings total 22.6 $tgCO_2e$ (fifth row). However, total fuel market leakage is positive because the RFS caused emissions from domestic gasoline and ROW crude to only fall by 16.6 $tgCO_2e$.

Table 7: Total Leakage from RFS

	2010	2012	2015
RFS (VEETC Renewed)			
Net Change in Emissions, *dGHG*	0.4	1.6	4.5
Intended Savings, *I*	3.0	5.0	9.7
Total Leakage	3.4	6.7	14.2
Total Land Market Leakage	1.3	3.5	8.2
Total Fuel Market Leakage	2.1	3.1	6.0
RFS (VEETC Swapped)			
Net Change in Emissions, *dGHG*	−5.4	−4.6	−2.0
Intended Savings, *I*	2.8	4.8	9.5
Total Leakage	−2.6	0.2	7.5
Total Land Market Leakage	1.2	3.5	8.1
Total Fuel Market Leakage	−3.8	−3.2	−0.6

Notes: All emissions categories are reported in tgCO_2e.

When the RFS is swapped for the RFS, total fuel market leakage is negative, following the reversal of the impact on blended fuel consumption. In 2012, total fuel market leakage is negative and strikingly large, −66.5% of intended emissions savings. In effect, fuel market adjustments from swapping the RFS for the VEETC generate additional emissions reductions that are about two-thirds the magnitude of the intended emissions savings. Due to the large reduction in blended fuel consumption when the RFS is swapped for the VEETC, negative leakage from domestic fuel adjustments is 127.0% of intended emissions savings and only a portion of this negative leakage is offset by positive leakage from the world crude oil market. Consistent with the larger expansion in world crude oil consumption when domestic blended fuel consumption contracts, leakage from the world crude market is 60.5% of intended emissions savings.

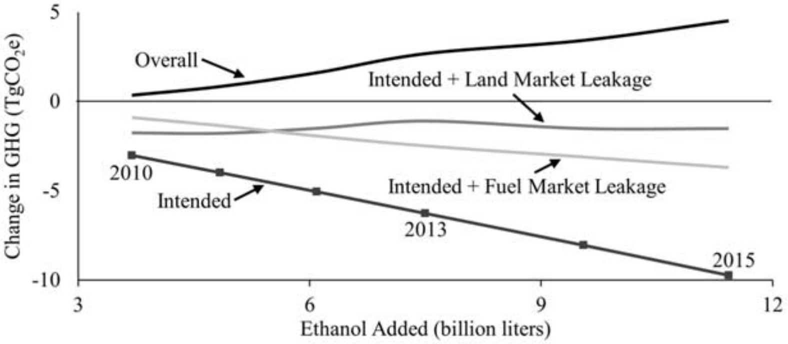
In 2015, total fuel market leakage remains negative, but is of a considerably smaller magnitude, only −6.8% of intended emissions savings. Here, negative leakage from the domestic fuel market is 57.5% of intended emissions savings, while positive leakage from the world crude oil market offsets 50.7%. This decline in negative leakage from the domestic fuel market is a result of both the decreasing reduction in blended fuel consumption and the doubling of intended emissions savings between 2012 and 2015.

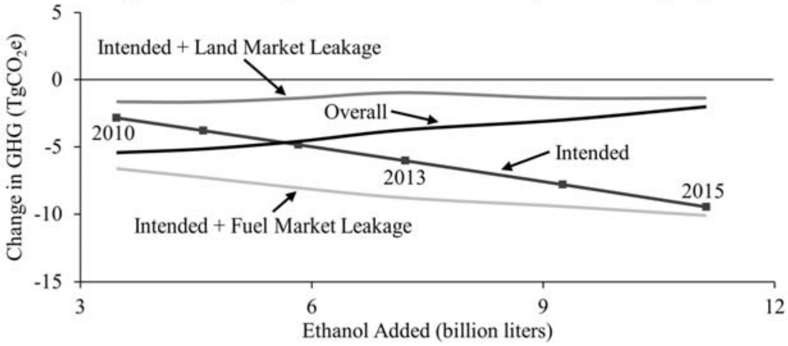
It is clear from Table 6 that leakage from the domestic fuel market exhibits considerable variability in both direction and magnitude. This is because the per liter emissions from gasoline are on the order of three times greater than the intended emissions savings of an energy equivalent quantity of ethanol (see Appendix Table A.7). As a result, leakage from domestic fuel markets proves to have a critical impact on the estimated emissions savings of the RFS. This is a key result of this paper, providing clear evidence for the need to carefully integrate both fuel and land markets in order to properly assess the emissions consequences of biofuel policies.

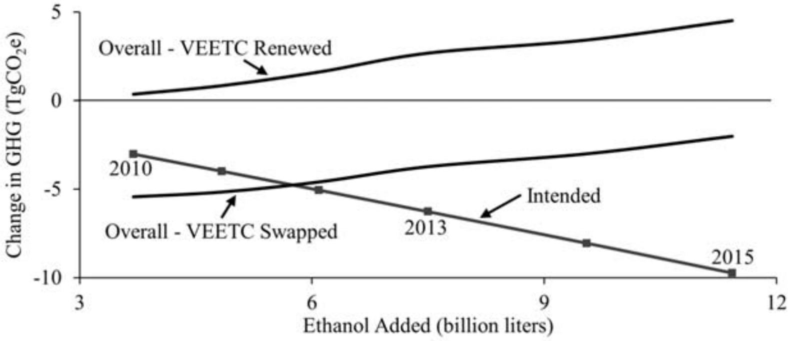
4.5 Will the RFS Reduce Emissions?

Table 7 decomposes, for the years 2010, 2012 and 2015, the net change in emissions due to the RFS into intended emissions savings and leakage, and breaks down total leakage into land and fuel market leakage following the analysis in Tables 4 and 6. Figure 1 graphically depicts these results for each year from 2010 to 2015. The first panel in Figure 1 illustrates how the overall change in emissions due to the RFS evolves as the amount of ethanol added by the RFS expands

Figure 1: Decomposition of Total Leakage


Panel 1. Decomposition of Change in GHGs due to the RFS (VEETC Renewed)


Panel 2. Decomposition of Change in GHGs due to the RFS (VEETC Swapped)


Panel 3. Overall Change in GHGs due to RFS – VEETC Renewed vs. VEETC Swapped

Notes: Change in emissions is relative to baseline with VEETC. Given that intended emissions savings are roughly equivalent whether or not the VEETC is renewed, only intended emissions savings with the VEETC renewed are displayed in Panel 3.

over time. The horizontal axis measures the quantity of ethanol added by the RFS for each year that the RFS binds, 2010 through 2015, relative to a baseline in which the VEETC is renewed. The vertical axis measures the resulting change in emissions.

The overall change in GHG emissions is depicted by the black line (without markers). Our central finding is that the RFS will increase GHG emissions relative to a baseline with the VEETC in place. Further, the increase in overall emissions becomes larger as the RFS mandates larger amounts of ethanol. In 2010, for an additional 3.7 billion liters of ethanol the RFS causes emissions to increase by 0.4 $tgCO_2e$ (Table 7). By 2015 the RFS causes ethanol to expand by 11.4 billion liters, corresponding to an emissions increase of 4.5 $tgCO_2e$.

The other three lines decompose the overall change in emissions into intended emissions savings, land market leakage and fuel market leakage. Intended emissions savings (labeled "Intended") exhibits a clear negative linear relationship with the ethanol added by the RFS. Intended emissions savings are 3.0 $tgCO_2e$ in 2010 and expand dramatically to 9.7 $tgCO_2e$ in 2015.

The line labeled "Intended + Land Market Leakage" depicts the sum of intended emissions savings and land market leakage. Thus, the vertical distance between this line and the intended emissions savings line represents net land market leakage, which is positive in each year. In 2010, if land market leakage is considered along with intended emissions savings, the RFS would only reduce emissions by 1.7 $tgCO_2e$, which is considerably less than intended emissions savings calculated using lifecycle methods. By 2015, despite intended emissions savings expanding greatly, emissions savings net of land market leakage falls to 1.5 $tgCO_2e$. This highlights that per liter of ethanol added by the RFS, land market leakage increases with the quantity of ethanol added by the RFS.[42] Domestic land supply is convex in the amount of corn land added by new ethanol due to the RFS, since corn yields are declining in the amount of acres under cultivation. Thus each marginal liter of ethanol added by the RFS has a larger impact on crop prices. As domestic land supply tightens, the contraction in crops demanded by the food sector and crop exporters becomes more severe, magnifying each source of land market leakage, particularly leakage from the world land market. Interestingly, this occurs despite crop yields and ethanol conversion efficiency improvements over time, which relieves some of this pressure.

The line labeled "Intended + Fuel Market Leakage" depicts the sum of intended emissions savings and fuel market leakage. This line falls above the intended emissions savings line because fuel market leakage due to the RFS is consistently positive when the VEETC is renewed. Intended emissions savings net of fuel market leakage is only 0.9 $tgCO_2e$ in 2010, but increases to 3.7 $tgCO_2e$ by 2015. Unlike land market leakage, fuel market leakage per liter of ethanol added by the RFS is roughly constant between 2010 and 2015 (see Appendix Table A.13).[43]

These results emphasize the importance of considering both land and fuel market leakage in a unified and consistent manner. Further, given that neither land nor fuel market leakage is sufficient to completely offset intended emissions savings, considering either source of leakage independently would result in a misleading conclusion that the RFS reduces emissions. In contrast, we find that the RFS unambiguously increases emissions.

The second panel in Figure 1 presents the same decomposition of GHG emissions as the first panel, when the RFS is swapped for the VEETC. Unlike the RFS when the VEETC is renewed, replacing the VEETC with the RFS can result in emissions reductions. In these two cases intended emissions savings and land market leakage are roughly identical, which is illustrated by the lines "Intended" and "Intended + Land Market Leakage" in the top two panels. In sharp contrast,

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[42] As reported in the Appendix Table A.13 land market leakage increase from 0.34 $kgCO_2e$ per liter additional ethanol in 2010 to 0.72 $kgCO_2e$ per liter in 2015.

[43] Per liter ethanol, total fuel market leakage remains constant over time because leakage from the domestic fuel market becomes less intensive offsetting intensification in leakage from the world crude market. The total increase in blended fuel, and leakage from the domestic fuel market, is roughly constant as more ethanol is added by the RFS because the increase in the price of ethanol remains in rough proportion to the fall in the price of gasoline. In contrast, leakage from the world crude oil market intensifies slightly because the excess supply of crude oil is convex, resulting in a larger reduction in the world price of crude oil for each additional liter of ethanol added by the RFS.

swapping the RFS for the VEETC results in negative fuel market leakage, which is illustrated by the “Intended + Fuel Market Leakage” line falling below the “Intended” line in each year.

In 2010, negative fuel market leakage dominates positive land market leakage. Thus, the overall reduction in emissions due to the RFS, 5.4 tgCO_2e, is greater than intended emissions savings of 2.8 tgCO_2e. In 2013 and after, the overall change in emissions, while still negative, is less then intended emissions savings. For example, in 2015 there is a net reduction in emissions of 2.0 tgCO_2e, while intended emissions savings are 9.5 tgCO_2e.

Although net fuel market leakage is negative for each of the ethanol volumes added by the RFS over time, it is declining in magnitude. This is illustrated by the vertical distance between the “Intended” and “Intended + Fuel Market Leakage” lines shrinking as the amount of ethanol added by the RFS expands. The impact of swapping the RFS for the VEETC on the price and quantity of blended fuel, and therefore the magnitude of leakage from the domestic fuel market, is roughly constant in each year. However, the same economic adjustments that result in negative domestic fuel market leakage, also imply world fuel market leakage to be larger at the margin. More gasoline displaced domestically corresponds to greater marginal world fuel market leakage, eroding the negative leakage from the domestic fuel market.. This suggests that studies that ignore leakage from fuel markets and interactions with pre-existing policies, such as the VEETC, will likely incorrectly estimate total leakage. Perhaps even more importantly, such studies could potentially miss the direction of the total change in emissions.

Swapping the VEETC with the RFS reduces emissions in each year, although this emissions reduction is contingent on the elevated level of emissions in the VEETC baseline. Thus, relative to the pre-2006 policy regime in which the VEETC was the dominant biofuel policy, the post-2011 policy regime in which just the RFS is the dominant biofuel policy implies more ethanol added to the economy and considerably fewer GHG emissions. The third panel of Figure 1 plots the overall change in emissions due to the RFS when the VEETC is renewed and when the VEETC is replaced by the RFS (the black lines from panels 1 and 2), as well as intended emissions savings. This graphically demonstrates the emissions implications of the decision to allow the VEETC to expire conditional on a binding RFS. Swapping the RFS for the VEETC leads to a parallel downward shift in the overall emissions curve. The resulting emissions savings are 6.5 tgCO_2e in 2015, and slightly lower for earlier years. This suggests that the decision to allow the VEETC to expire at the end of 2011 will have resulted in cumulative emissions savings of 25.5 tgCO_2e by 2015.[44]

4.6 Limits to Emissions Savings From Swapping RFS for VEETC

The third panel of Figure 1 also suggests that there are limits for the switch in policy regimes from VEETC to RFS to achieve both an increase in ethanol and a reduction in emissions. If, as some policymakers have recently suggested, the conventional RFS was expanded to compensate for the inability of the U.S. to meet the advanced RFS, there will likely be mandated volumes of corn ethanol for which emissions will increase. A simple extrapolation of the overall emissions curve suggests that replacing the RFS with the VEETC will start to increase overall emissions when more than 15.6 billion liters of ethanol are added by the RFS. After this point, replacing the VEETC

[44] The reduction in emissions identified here should not be attributed to imposing just the RFS or eliminating just the VEETC. Rather it corresponds to the emissions savings achieved from eliminating the VEETC conditional on the RFS binding.

Table 8: Total Leakage from RFS Relative to No-VEETC Baseline

	2010	2012	2015
Ethanol Baseline, No VEETC (billion liters)	22.7	24.5	31.2
Change in Ethanol due to RFS	23.0	25.8	25.8
Net Change in Emissions (tgCO2e), *dGHG*	6.8	7.0	6.7
Intended Savings, *I*	19.3	22.1	22.4
Total Leakage	26.1	29.1	29.1
Total Land Market Leakage	12.5	14.0	14.3
Total Fuel Market Leakage	13.6	15.1	14.9

with the RFS will imply a fundamental trade-off between ethanol expansion and increased emissions.

4.7 Impacts of Eliminating the RFS Now that the VEETC Has Expired

As discussed earlier, the RFS Elimination Act has proposed eliminating the RFS for conventional biofuels. Given that the VEETC has expired, elimination of the RFS at this point will entail moving to a regime where there is no large-scale support program in place for corn ethanol. Table 8 presents the change in ethanol, intended emissions savings and leakage due to the RFS relative to a baseline that does not include the VEETC for the years 2010, 2012 and 2015. Examination of this case suggests the implications from moving from the current, post-2011 regime in which just the RFS is in place to a new regime where the RFS has been eliminated and the VEETC is not resurrected.

Relative to the no-VEETC baseline, the RFS results in greater GHG emissions. In 2010, the RFS causes ethanol to increase by 23.0 billion liters and emissions to increase by 6.8 tgCO_2e. By 2015 the RFS causes ethanol to expand by 25.8 billion liters, corresponding to an emissions increase of 6.7 tgCO_2e. Consequently, eliminating the RFS would provide a modest emissions reduction.

The increase in emissions in this case are larger than those of the RFS relative to the baseline that includes the VEETC, when the VEETC is renewed, mostly because the RFS has a considerably larger impact on ethanol. However, leakage and the net change in emissions are not proportional to the change in ethanol quantities. Appendix Table A.15 reports the emissions impacts per liter of ethanol added by the RFS relative to the no-VEETC baseline. The corresponding results for the RFS relative to the VEETC baseline are reported in Appendix Table A.13. Per liter of ethanol added by the RFS in 2015, land market leakage is greater when the RFS is compared to the VEETC baseline (0.72 kgCO_2e/liter) than when the RFS is compared to the baseline without VEETC (0.55 kgCO_2e/liter). Conversely, fuel market leakage per liter of ethanol added by the RFS is smaller when comparing to the VEETC baseline, 0.53 kgCO_2e/liter, than when comparing to the no VEETC baseline, 0.58 kgCO_2e/liter. These two observations illustrate the critical manner in which land market and fuel market leakage are jointly determined, and that leakage in both markets will depend on the choice of policy baseline.

The baseline quantity of ethanol, and therefore corn, is lower in the no-VEETC baseline. Since the RFS adds ethanol to a slacker land market in this instance, land market leakage per liter of ethanol added is smaller in this case. In contrast, the VEETC in the baseline serves to elevate the amount of ethanol and corn in the baseline, so that the additional ethanol added by the RFS relative to this baseline corresponds to larger impacts on crop prices and land market leakage at the margin. The same economic forces that drive this differential land market leakage at the margin also correspond to a larger increase in the price of ethanol and thus a smaller decrease in the price of blended fuel at the margin. As a result, domestic fuel market leakage per liter of ethanol added by the RFS is smaller when evaluating the RFS relative to a baseline that includes the VEETC than when assessing the RFS relative to the baseline without the VEETC.

The same increase in corn prices that affects land market leakage at the margin also translates into a greater increase in the price of ethanol and a smaller decrease in the price of blended fuel at the margin. As a result, domestic fuel market leakage is smaller for the VEETC renewed case than when assessing the impact of the RFS relative to the baseline without the VEETC.

4.8 Benefits of a Unified Framework of Land and Fuel Markets

A common approach in the literature (Thompson, Whistance, and Meyer 2011; Rajagopal and Plevin 2013) has been to evaluate the implications of biofuel policies assuming constant land market adjustments and/or emissions factors. While direct comparisons to the literature are difficult due to differences in policies being examined, time-horizon of evaluation as well as other modeling assumptions, we can get at the implications of this assumption in the context of our own analysis which allows us to hold such assumptions fixed. For example, we can re-evaluate the emissions savings of the RFS relative to a baseline in which the VEETC is in place, by imposing the per liter land market leakage implied by our analysis of the RFS relative to a baseline without the VEETC, and vice-versa. Doing so would imply that per liter emissions due to the RFS would fall from 0.40 to 0.23 kgCO_2e/liter for the case when the VEETC is included in the baseline. Thus, the RFS would increase emissions by 41.8% less than our central result. In contrast, performing the same analysis in reverse for the RFS relative to the baseline without the VEETC results in a total change in emissions due to the RFS that is 63.6% larger than our central result. Although this analysis relies on a simple back of the envelope calculation, it demonstrates how differences in policy regime can affect average land market leakage and highlights limitations of many prior analyses.

4.9 Sensitivity Analysis

We perform a comprehensive sensitivity analysis of the emissions impacts of the RFS for conventional biofuels for our two central policy regimes. Table 9 reports the impact of the RFS on emissions by varying two alternative sets of parameters that primarily impact adjustments in fuel markets: the elasticity of excess supply of crude oil and the elasticities of demand for blended fuel and VMT with respect to the price of fuel. Table 10 evaluates the implications of varying two sets of parameters that primarily affect adjustments in land markets: the elasticities of crop demand for domestic food production and the agricultural and land use emissions factors. Both tables focus exclusively on 2015, report the baseline amount of ethanol, the change in ethanol induced by the RFS, and emissions and leakage terms per liter of ethanol added by the RFS. Details on the parameter cases being varied are provided at the bottom of each table. To ease comparison, we re-state the emissions outcomes for the central parameter assumptions in the first column in both tables. For the sake of brevity, we emphasize the results from varying the blended fuel and VMT elasticities from Table 9 and the elasticities of crop demand for food production from Table 10. Additional results for these cases in 2012 are provided in Appendix Tables A.16 and A.17. Appendix Table A.18 reports sensitivity analysis that vary the energy and corn requirements of ethanol production,

Table 9: Emissions in 2015 Under Alternative Parameter Assumptions, Fuel Markets

Crude Oil Excess Supply Elasticity Fuel and VMT Elasticity of Demand	Central Central	Low Central	High Central	Central Low	Central High
RFS (VEETC Renewed)					
Baseline Ethanol Consumption (billion liters)	45.4	46.8	44.7	46.4	44.4
Change in Ethanol Consumption	11.4	10.2	12.0	10.3	12.5
Net Change in Emissions (kgCO_2e/liter ethanol added)	0.40	0.79	0.22	0.34	0.44
Intended Savings, I	0.85	0.85	0.85	0.85	0.85
Domestic Land Market Leakage, L^{DA}	−0.07	−0.05	−0.08	−0.07	−0.08
World Land Market Leakage, L^{WA}	0.79	0.80	0.79	0.80	0.78
Domestic Fuel Market Leakage, L^{DF}	0.22	0.64	0.02	0.14	0.28
World Fuel Market Leakage, L^{WF}	0.31	0.25	0.34	0.32	0.31
RFS (VEETC Swapped)					
Baseline Ethanol Consumption (billion liters)	45.4	46.8	44.7	46.4	44.4
Change in Ethanol Consumption	11.1	9.9	11.7	10.1	12.0
Net Change in Emissions (kgCO_2e/liter ethanol added)	−0.18	0.28	−0.38	−0.11	−0.24
Intended Savings, I	0.85	0.85	0.85	0.85	0.85
Domestic Land Market Leakage, L^{DA}	−0.07	−0.05	−0.08	−0.06	−0.07
World Land Market Leakage, L^{WA}	0.80	0.81	0.79	0.81	0.79
Domestic Fuel Market Leakage, L^{DF}	−0.49	0.02	−0.72	−0.42	−0.56
World Fuel Market Leakage, L^{WF}	0.43	0.35	0.47	0.41	0.45

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

in light of research suggesting that the efficiency and lifecycle emissions of ethanol production has been improving over time (Liska et al. 2009).

More elastic fuel and VMT demand imply larger increases in emissions for the RFS when the VEETC is renewed, but larger reductions in emissions when the RFS replaces the VEETC.[45] This result arises because both demand for VMT and blended fuel are more responsive to changes in the price of blended fuel. Consequently, both the fall in the price of blended fuel due to the RFS when the VEETC is renewed and the increase in the price of blended fuel that results when the RFS replaces the VEETC are larger. This increases the magnitude of domestic fuel market leakage in both cases although it has no impact on the direction of leakage. Land market leakage is relatively unaffected by changes in the elasticities of fuel and VMT demand because the RFS sets the level of ethanol in the economy, which causes corn to increase by a fixed quantity.

Increasing the elasticities of crop demand for domestic food production implies a smaller increase in crop prices as a result of the RFS.[46] This increases the magnitude of negative domestic land market leakage and decreases the magnitude of positive leakage from the world land market, resulting in lower land market leakage overall. In addition, increasing these elasticities causes the

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[45] The high case jointly increases the elasticities of blended fuel and VMT demand by 0.1 from their central values of 0.3 and 0.2, respectively, whereas the low case considers a joint decrease in both elasticities by 0.1. This is achieved by modifying the elasticities of substitution, σ_U, σ_W, and σ_M in equation A.5 in the Appendix.

[46] The low and high cases are constructed by halving and doubling the elasticities of substitution, σ_X, σ_Q and σ_V, in equation A.14 in the Appendix.

Table 10: Emissions in 2015 Under Alternative Parameter Assumptions, Land Markets

Elasticities of Crop Demand for Food Production Agriculture and Land Use Emissions	Central Central	Low Central	High Central	Central Low	Central High
RFS (VEETC Renewed)					
Baseline Ethanol Consumption (billion liters)	45.4	43.2	49.7	45.4	45.4
Change in Ethanol Consumption	11.4	13.6	7.1	11.4	11.4
Net Change in Emissions (kgCO$_2$e/liter ethanol added)	0.40	0.51	0.27	−0.09	1.32
Intended Savings, I	0.85	0.85	0.85	0.90	0.43
Domestic Land Market Leakage, L^{DA}	−0.07	0.03	−0.20	−0.18	−0.02
World Land Market Leakage , L^{WA}	0.79	0.88	0.72	0.46	1.24
Domestic Fuel Market Leakage, L^{DF}	0.22	0.12	0.30	0.22	0.22
World Fuel Market Leakage, L^{WF}	0.31	0.33	0.30	0.31	0.31
RFS (VEETC Swapped)					
Baseline Ethanol Consumption (billion liters)	45.4	43.2	49.7	45.4	45.4
Change in Ethanol Consumption	11.1	13.2	6.7	11.1	11.1
Net Change in Emissions (kgCO$_2$e/liter ethanol added)	−0.18	0.03	−0.68	−0.67	0.75
Intended Savings, I	0.85	0.85	0.85	0.90	0.43
Domestic Land Market Leakage, L^{DA}	−0.07	0.04	−0.20	−0.17	−0.02
World Land Market Leakage , L^{WA}	0.80	0.89	0.73	0.47	1.25
Domestic Fuel Market Leakage, L^{DF}	−0.49	−0.47	−0.86	−0.49	−0.49
World Fuel Market Leakage, L^{WF}	0.43	0.42	0.50	0.43	0.43

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

residual supply of corn available for ethanol production (e.g. total corn supply less corn demanded by exporters and domestic food producers) to become more elastic. Therefore, the increase in the price of ethanol due to the RFS is softened, implying a larger fall in the price of blended fuel for the RFS when the VEETC is renewed and a smaller decrease in the price of blended fuel when the RFS is swapped for the VEETC. Accordingly, positive domestic fuel market leakage increases in magnitude for the former, but negative domestic fuel market leakage declines in magnitude for the latter. However, world fuel market leakage decreases in magnitude for both. Cumulatively, more elastic crop demand implies a smaller increase in emissions due to the RFS when the VEETC is renewed and a larger reduction in emissions when the RFS replaces the VEETC.[47]

Comparing the results of these two analyses provides a very illuminating insight regarding the mechanisms through which both land and fuel market leakage are co-determined. Varying parameters that impact primarily fuel markets, such as varying the elasticities of fuel and VMT demand, implies little change in land market leakage largely because blended fuel is not an input in crop production. The only extent that land market leakage is affected when we vary fuel market parameters is when adjusting these parameters impacts the ethanol baseline. In this case land market leakage is marginally affected owing principally to our earlier observation regarding the addition of ethanol to ever tighter land markets. In sharp contrast, varying parameters that primarily impact

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[47] The crop demand elasticities for domestic food production also have a significant impact on the baseline quantity of ethanol in 2015. As a result, some of the leakage values per liter ethanol added do not follow expected patterns because the quantity of ethanol added by the RFS varies across sensitivity runs.

Table 11: Range of Emissions in 2015

Parameter Case	Best	Worst
Crude Oil Excess Supply Elasticity	High	Low
Fuel and VMT Elasticities of Demand	Low/High	High/Low
Elasticities of Crop Demand for Food Production	High	Low
Agriculture and Land Use Emissions	Low	High
RFS (VEETC Renewed)		
Baseline Ethanol Consumption (billion liters)	50.0	43.3
Change in Ethanol Consumption	6.8	13.8
Net Change in Emissions (kgCO$_2$e/liter ethanol added)	−0.32	2.01
Intended Savings, I	0.90	0.42
Domestic Land Market Leakage, L^{DA}	−0.23	0.18
World Land Market Leakage , L^{WA}	0.43	1.37
Domestic Fuel Market Leakage, L^{DF}	0.05	0.65
World Fuel Market Leakage, L^{WF}	0.33	0.24
RFS (VEETC Swapped)		
Baseline Ethanol Consumption (billion liters)	48.0	45.7
Change in Ethanol Consumption	8.3	11.0
Net Change in Emissions (kgCO$_2$e/liter ethanol added)	−1.36	1.62
Intended Savings, I	0.90	0.42
Domestic Land Market Leakage, L^{DA}	−0.24	0.23
World Land Market Leakage , L^{WA}	0.41	1.45
Domestic Fuel Market Leakage, L^{DF}	−1.21	0.02
World Fuel Market Leakage, L^{WF}	0.57	0.34

Notes: For the RFS when the VEETC is renewed, the fuel and VMT elasticities of demand are set to the low values in the best case and to the high values in the worst case. When the RFS is swapped for the RFS, the fuel and VMT elasticities of demand are set to the high values in the best case and to the low values in the worst case.

land markets, such as the elasticities of crop demand for domestic food production, impacts both land and fuel market leakage because these parameters directly impact the equilibrium price of corn which is effectively an input in the production of blended fuel.

4.9.1 Bounds of Emissions Results

Although not reported here, we explored emissions results under all 81 combinations of the four sets of sensitivity assumptions. Emissions increase in 63 out of 81 cases (78%) when the VEETC is renewed, which suggests our central finding that the RFS causes emissions to increase is robust. When the RFS is swapped for the VEETC, emissions decrease in 48 out of 81 cases (59%), which suggests that our central result that swapping the VEETC with the RFS will result in fewer emissions is not nearly as robust.[48] Table 11 reports the best and worst cases for the change in emissions per liter of ethanol added across all 81 parameter combinations in 2015.[49] When the

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[48] In 2012 we find that the RFS will increase emissions under 61 parameter combinations if the VEETC is renewed. Swapping the VEETC with the RFS, however, will reduce emissions for 65 parameter combinations. This is because the land market leakage and world fuel market leakage is substantially smaller in 2012 compared to 2015, while domestic fuel market leakage is of the same gross magnitude.

[49] The best case uses the high elasticity of crude oil supply, the high crop demand elasticities for domestic food production and the low agricultural and land use emissions, both for the RFS when the VEETC is renewed and when the RFS is swapped for the VEETC. Since varying the fuel and VMT elasticities cause the total change in emissions due to the

VEETC is renewed, the RFS reduces emissions by 0.32 kgCO_2e per liter of ethanol added in the best case, but increases emissions by 2.01 kgCO_2e per liter of ethanol added in the worst case. The worst case is a five-fold increase over the central results. When the RFS is swapped for the VEETC, the reduction in emissions is at best 1.36 kgCO_2e per liter of ethanol added, a six-fold greater decline in emissions than our central result for this case. At worst, net emissions increase by 1.62 kgCO_2e per liter of ethanol added.[50]

5. CONCLUSION

This paper developed a multi-market economic model that integrates fuel, land and food markets and is linked with a disaggregated emissions model to examine the effects of the RFS for conventional biofuels on GHG emissions. The framework allows for both positive and negative leakage to arise from changes in policy regimes. These features are crucial for evaluating incomplete climate legislation because interactions between policies resulting from changes in policy regimes can impact the magnitude and direction of leakage.

Our central finding is that the expansion of biofuels mandated by the RFS can increase or decrease GHG emissions depending on the policy regime being evaluated. Relative to a baseline that includes the VEETC, which was in place when the current RFS was established, the RFS causes emissions to increase by 4.5 tgCO_2e in 2015. However, swapping the RFS for the VEETC implies fewer GHG emissions than those that result from the VEETC itself, causing emissions to fall by 2.0 tgCO_2e in 2015. Thus, the decision to allow the VEETC to expire at the end of 2011 will result in cumulative emissions savings of 25.5 tgCO_2e between 2012 and 2015, while increasing ethanol production considerably. Finally, the RFS causes emissions to increase by 6.7 tgCO_2e in 2015 when evaluated relative to a baseline without the VEETC. Given that the VEETC has expired, this is also the amount by which emissions could be reduced if the RFS for conventional biofuels was eliminated, although a full cost-benefit analysis, along the lines of Chen et al. (2011), Lapan and Moschini (2012), or Bento and Landry (2014), would be needed before making such a significant policy change.

While the overall impact on emissions of the policy regimes we consider are modest, our numerical analysis uncovers two surprising results that could not be inferred from a theoretical exercise, an analysis of a single market alone, or a multi-market analysis that uses constant emissions factors in one of the markets. First, both baselines and policy context matter when determining the change in overall GHG emissions and the contributions of each leakage channel. The RFS alone increases emissions relative to both a baseline that includes the VEETC and a baseline that does not include the VEETC. However, per liter of ethanol added by the RFS, land market leakage is smaller and fuel market leakage greater when assessing the impact of the RFS relative to a no-VEETC baseline than when performing the same analysis in relation of a baseline that includes the VEETC. Critically, this reveals how emissions from one leakage channel are co-determined with emissions from another leakage channel through linked markets. The difference between the two

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RFS to move in opposite directions depending upon the policy context being considered, low elasticities of fuel and VMT demand are used for the RFS when the VEETC is renewed and high values are used for these elasticities when the RFS is swapped for the VEETC. The worst case is the reverse of these parameter combinations.

[50] Although not reported for space considerations, we conduct an identical sensitivity analysis for the RFS relative to a baseline without the VEETC. In 2015, we find that the RFS increases emissions in 58 of the 81 parameter cases (71%) in 2015. The emissions impacts per liter ethanol added by the RFS range from a decrease of 0.47 kgCO_2e/liter to an increase of 1.72 kgCO_2e/liter.

cases results from the impact of the VEETC on the baseline, with the RFS causing less ethanol to be added to a tighter market when comparing to a baseline that includes the VEETC then when comparing to a baseline without the VEETC. Relatedly, swapping the RFS for the VEETC implies fewer GHG emissions than those that result from the VEETC alone, which illustrates that pre-existing policies can lead to reversals in the direction of leakage and the overall change in GHG emissions.

Second, we show that there is an implicit tension between land and fuel market leakage channels. Policy regimes that result in less land market leakage tend to result in more domestic fuel market leakage per liter of ethanol added. Likewise, sensitivity analysis on the elasticity of crop demand for food production illustrates that assumptions regarding economic responses that will dampen land market leakage can exacerbate fuel market leakage. This tension reaffirms that the leakage channels are co-determined and that jointly modeling land and fuel markets is critical to understanding the emissions impact of the RFS. The relationship between land and fuel market leakage has important implications for policy since it suggests that due to price effects, different types of policy instruments may lead to different leakage magnitudes. Therefore, this tension should be considered when evaluating other policies that support biofuels.

An important caveat concerns our numerical results. Our simple treatment of the rest of the world, which was necessary for simplicity and tractability, may limit our ability to precisely quantify leakage from world land and crude oil markets. Quantifying the world land use impacts of U.S. biofuel policies remains a first-order research priority, but is not the purpose of this paper. Analyses that rely on global equilibrium models have generated a wide range of estimates (EPA 2010a; Hertel, Tyner, and Birur 2010; Searchinger et al. 2008; Dumortier et al. 2011). This points to the need for more detailed country or regional analyses in the style of Barr et al. (2011). Our estimates of world land use change resulting from expanded biofuels production in the U.S. fall centrally in the range of these published estimates and our main results hold under a range of parameter assumptions. We recognize that our framework does not explicitly model the demand for crude products other than gasoline consumed in the U.S. or any substitutes for crude oil products, and does not account directly for the complexities of the crude oil market, such as potential market power of crude oil suppliers or refineries.

Moving forward, policymakers are considering advanced biofuels and other incomplete climate legislation, such as renewable portfolio standards. Broadly speaking, our findings imply that, the sources of leakage identified here are likely to be present in such proposals, compromising their ability to reduce GHG emissions.

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