Alternative Transportation Fuel Standards: Welfare Effects and Climate Benefits

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This paper develops an integrated model of the fuel and agricultural sectors to analyze the welfare and greenhouse gas emission (GHG) effects of the existing Renewable Fuel Standard (RFS), a Low Carbon Fuel Standard (LCFS) and a carbon price policy. The conceptual framework shows that these policies differ in the incentives they create for the consumption and mix of different types of biofuels and in their effects on food and fuel prices and GHG emissions. We also simulate the welfare and GHG effects of these three policies which are normalized to achieve the same level of US GHG emissions. By promoting greater production of food-crop based biofuels, the RFS is found to lead to a larger reduction in fossil fuel use but also a larger increase in food prices and a smaller reduction in global GHG emissions compared to the LCFS and carbon tax. All three policies increase US social welfare compared to a no-biofuel baseline scenario due to improved terms-of-trade, even when environmental benefits are excluded; global social welfare increases with a carbon tax but decreases with the RFS and LCFS due to the efficiency costs imposed by these policies, even after including the benefits of mitigating GHG emissions.

Introduction

Concerns about greenhouse gas (GHG) emissions and the desire to reduce dependence on foreign oil have led to support for policy strategies targeted directly at promoting low carbon biofuels in the United States (US) (DOT, 2010). While renewable fuels for transportation are currently limited to first-generation biofuels produced primarily from corn in the US and sugarcane in Brazil, there is growing emphasis on inducing a shift to a new generation of advanced biofuels. Unlike first-generation biofuels, second-generation biofuels can potentially be produced from a variety of feedstocks, such as crop and forest residues and dedicated energy crops, like miscanthus and switchgrass. While advanced biofuels are yet to be produced commercially, studies indicate that high-yielding energy crops can be grown productively on low quality land and that these biofuels have significantly lower (even negative) GHG intensity than fossil fuels and first-generation biofuels (Gelfand et al., 2013; Tilman et al., 2009).
Policies to induce biofuel production in the US include technology (biofuel) mandates and performance-based standards for transportation fuel. The former has taken the form of the Renewable Fuel Standard (RFS) established by the Energy Independence and Security Act (EISA) of 2007, which sets annual volumetric (quantity-based) targets for the blending of specific types of biofuels with fossil fuels based on their life-cycle GHG intensity. A Low Carbon Fuel Standard (LCFS) is a performance-based standard to reduce the GHG intensity of transportation fuel. A national LCFS to reduce GHG intensity of transportation fuel by 10% by 2020 was among the early proposals for promoting low carbon fuels in the US in 2008.1

In contrast to these policies, a carbon price policy could be used to directly target a reduction in GHG emissions.

By explicitly or implicitly imposing taxes or providing subsidies, these policies affect the relative prices of various biofuels and fossil fuels. With the potential to produce different types of first- and second-generation biofuels that differ in their land requirements, GHG intensity and costs of production, these policies will differ in the extent to which they induce biofuel consumption and in the mix of biofuels induced. These policies will, therefore, vary in the extent to which they will divert land from food/feed production and adversely affect crop prices.

The volume and mix of biofuels will also directly affect the extent to which fossil fuels are displaced and the GHG intensity of the resulting fuel mix. Additionally, biofuels will affect GHG emissions indirectly by affecting food and fuel prices.2 Increased food prices could lead to indirect land use change (ILUC) that occurs as cropland expands and releases stored carbon in soils and vegetation globally; this leakage effect will affect the net GHG savings achieved by inducing more biofuel production. The magnitude of the ILUC effect will vary with the quantity and mix of biofuels and, thus, across policies; cellulosic biofuels produced from crop residues or energy grasses grown on less productive/marginal land will have a smaller impact on food crop prices than food crop-based biofuels. Moreover, by lowering the demand for fossil fuels in the US these policies have the potential to decrease the price of fuel in the world market. This could lead to a rebound in fossil fuel consumption in the US and the rest of the world (ROW), such that biofuels displace less than the energy equivalent amount of fossil fuels and offset a part of the GHG savings with biofuels.

This paper develops an integrated model of the fuel and food sectors to compare these effects of a biofuel mandate, a LCFS and a carbon tax on the mix of biofuels and fossil fuels, land use changes, and on food and fuel prices. We first present a simple conceptual framework to analyze the differential mechanisms by which these policies affect food and fuel consumption and GHG emissions and identify some of the key parameters in the food and fuel sectors likely to influence these outcomes. We then quantify these effects over the 2007–2030 period using a partial equilibrium, open economy, dynamic model of the fuel and agricultural sectors of the US (Biofuel and Environmental Policy Analysis Model (BEPAM)). We select the GHG intensity reduction targets for the LCFS and the carbon tax rate to achieve the same level of US GHG emissions as the RFS over the 2007–2030 period to obtain comparable outcomes under these three policies. Even though their impact on domestic GHG emissions are normalized to be the same, these policies can differ in their impact on global emissions because of the differences in their impact on global food and fuel prices, and thus on fuel consumption by the ROW and on the international ILUC.

Furthermore, we compare the welfare effects of these three policies both for the US and for the ROW. By inducing consumption of high cost biofuels beyond the free market level, these policies impose efficiency costs on the domestic food and fuel sectors. In a closed economy, these policies will impose a net economic cost, relative to a no-policy (laissez-faire) scenario, with the carbon tax inducing the lowest-cost mix of GHG abatement strategies unlike a mandate and GHG intensity standard that limit the flexibility of abatement options. However, in an open economy, these policies could improve the terms-of-trade for the US to varying degrees depending on the extent to which they raise the prices of agricultural exports and lower the price of fuel imports. This would shift a part of the costs of biofuel policies to trading partners (causing them to be referred to as “beggar-thy-neighbor” policies) (Böhringer and Rutherford, 2002), thereby offsetting their efficiency costs relative to the no-policy scenario (Moschini et al., 2010). These policies could therefore lead to positive net economic benefits in the US (even without including their environmental benefits), however their magnitudes need to be compared empirically after incorporating the potential for the efficiency costs to decline over time with improvements in the industrial costs of producing advanced biofuels and growth in biofuel feedstock yields (Chen et al., 2012). Moreover, these biofuel and climate policies implemented in the US could have different impacts on the ROW. We examine the distributional effects of these policies on food and fuel consumers and producers both in the US and the ROW. We consider the potential for cost reducing technological change in biofuel production due to learning-by-doing and its implications for the welfare costs of alternative policies. Lastly, we consider the possibility that the LCFS and carbon tax policy could coexist with the RFS and compare the welfare and GHG effects of implementing these policies together to those with the RFS alone.

Several studies have used stylized models of the fuel sector to analyze the effects of policies to induce the production of corn ethanol on GHG emissions. de Gorter and Just (2009) and de Gorter and Just (2008) analyze the effects of various policies such as a biofuel mandate, tax credit and import tariffs on fuel prices while Khanna et al. (2008) compare the effects of a mandate and tax credit on GHG emissions. Rajagopal et al. (2011), Drabik and de Gorter (2011), and Thompson et al.

1 http://usliberals.about.com/od/environmentalconcerns/a/ObamaEnergy_2.htm. Since then, a state-wide LCFS has been established in California, which requires a 10% reduction in the GHG intensity of transportation fuels sold in the state by 2020. Many other states have also proposed regional or state-level LCFS and a proposal for a national LCFS was also included initially in the proposed American Clean Energy Security Act in 2009.

2 Holland (2012) discusses the optimal selection of emissions taxes and intensity standards with and without leakage, and show that in the presence of emissions leakage an intensity standard can dominate the optimal emissions taxes.
(2011) analyze the effect of corn ethanol mandate and tax credit on fuel use and emissions leakage in the fuel market and show that these effects differ across policies.

The previous studies analyzing the welfare and GHG effects of a biofuel mandate (Ando et al., 2010) and a LCFS (Holland et al., 2009) have considered the US as a closed economy. They show that while the effect of these policies on emissions is ambiguous, they lead to lower social welfare than an optimal policy that internalizes various externalities. Lapan and Moschini (2012) consider the US as an open economy and show conditions under which a mandate with and without a tax credit can lead to a gain in social welfare by improving the terms-of-trade relative to a no-policy baseline, even if the externality benefits are excluded. Cui et al. (2011) also find that the status quo mandate and tax credit policies lead to a net gain in social welfare relative to a no-policy baseline but to lower welfare than a first best policy. These studies, however, do not directly compare the three policies considered here. They also do not include the diverse mix of second-generation biofuels considered in this study which increases the contrast in the performance of these policies.

The effect of biofuel policies, specifically the RFS, on land use and food prices has been examined by several studies using large-scale open-economy numerical models. Hertel et al. (2010) and Searchinger et al. (2008) use the Global Trade Analysis Project (GTAP) and Food and Agricultural Policy Research Institute (FAPRI) models, respectively, to examine the direct and indirect land use changes due to the mandate for corn ethanol. Hertel et al. (2010) show that the terms-of-trade effect of corn ethanol mandate in the US and of EU biofuel policies partially offset the allocative efficiency costs of these policies. These studies have focused on analyzing the effects of first-generation biofuels only and on estimating the GHG emissions due to the biofuel-induced land use change only; they did not consider the life-cycle GHG emissions from fuel use and other production activities impacted by biofuel production. Similarly, Bento et al. (forthcoming) analyze the effects of the corn ethanol mandate and show that in the presence of a biofuel tax credit, it will reduce US GHG emissions but increase global emissions. Studies that analyze the effects of the RFS while considering a mix of first- and second-generation biofuels include Beach and McCarl (2010) and Khanna et al. (2011). The former uses the Forest and Agricultural Sector Optimization Model (FASOM) while the latter used an earlier version of BEPAM to analyze the least cost mix of alternative biofuels to meet the RFS and their GHG implications.3

This paper extends previous studies by applying an integrated framework of the food and fuel sectors to compare the market and social welfare effects of the RFS, LCFS and carbon tax policy that achieve the same level of domestic life-cycle GHG emissions as the RFS. It includes food and fuel markets to assess the welfare effects of these normalized policies for both the domestic food and fuel consumers and producers and for those in the ROW and compares the global costs and benefits of these policies. The framework presented here explicitly models the demand for biofuels based on the vehicle fleet structure; this enables the demand for biofuels and fossil fuel to be derived from the demand for vehicle miles traveled (VMT) and to evolve over time depending on the changes in the vehicle fleet structure and in fuel efficiency standards. The fuel sector includes both gasoline and diesel markets both domestically and in the ROW as well as a broad set of first- and second-generation biofuels including ligno-cellulosic ethanol and biomass-to-liquids (BTL) diesel that can be blended with gasoline and diesel, respectively. The agricultural sector includes various cellulosic feedstocks for biofuel production, and considers competition between food and fuel crops for cropland at a fine spatial resolution, which enables us to compare the differential effects of these policies on food prices and land use. The agricultural sector also includes domestic and global demand and supply of various tradable agricultural commodities. We apply this framework to analyze the trade-offs posed by these policies among the objectives of achieving energy security by reducing gasoline imports, mitigating global GHG emissions and their economic impact.

Conceptual framework

We consider an economy with a representative consumer who demands food (f) and VMT (represented by m). The latter are produced by blending gasoline (g) and biofuels (e) as perfect substitutes in the production of VMT. The production of VMT can be expressed as \( m = rg + \beta e \), where \( r \) is an efficiency parameter denoting the quantity of miles produced from one gallon of gasoline equivalent energy and \( 0 < \beta < 1 \) is energy content of per gallon of biofuels relative to a gallon of gasoline.

We consider two types of biofuels, one high carbon biofuel \( e_H \) and another low carbon biofuel \( e_L \), which differ not only in their GHG intensity but also in their yield per acre of land4, thus \( e = e_H + e_L \). Let \( \delta_2, \delta_H, \delta_L \) denote the GHG emissions generated per gallon of gasoline, \( e_H \) and \( e_L \). We assume \( \beta \delta_2 > \delta_H > \delta_L \), which indicates that a gallon of gasoline emits more GHG emissions than a gallon of energy equivalent biofuel. Aggregate GHG emissions \( Z = \delta_g g + \delta_H e_H + \delta_L e_L \). Both gasoline and biofuels generate other negative externalities as well, including congestion, air pollution, and accidents while biofuels also generate a positive externality, such as energy security. These are not considered here for simplicity, but the framework could be readily expanded to include them.

3 Khanna et al. (2011) applied an earlier version of BEPAM to simulate supply curves of various cellulosic feedstocks to produce one billion tons of biomass by 2030 while Chen and Khanna (2012) used it to quantify the rebound effects of the RFS, LCFS and carbon tax policies in the fuel market with exogenously given policy targets. Huang et al. (2013) applied BEPAM to examine the welfare effects of stacking alternative policies such as the LCFS and a carbon tax on the RFS and its effects on GHG savings compared to the RFS alone.

4 One can consider \( e_H \) as corn ethanol, and \( e_L \) as cellulosic ethanol. Corn ethanol is both more carbon intensive and more land intensive than cellulosic ethanol from energy crops like miscanthus (Khanna and Crago, 2012). In the numerical simulation model, we relax this assumption by considering several types of biofuels that differ in their land intensity and GHG intensity.
We use \( p_m(.) \) and \( p_f(.) \) to denote the inverse demand functions for VMT and food, respectively, and assume they are continuous, differentiable and downward-sloping. We simplify our analysis here by assuming that the consumer surplus derived from food and VMT is additive (as in Chakravorty et al. (2008)). The sum of areas underneath the inverse demand functions of VMT and food is \( \int_0^m p_m(.)d(.) + \int_0^f p_f(.)d(.) \), where \( .(.) \) denotes integration variables.

We assume agricultural land is the only input used to produce food and biofuels, and that it is homogenous in quality with a given endowment of \( L \). We denote the land dedicated to the production of food and biofuels by \( L_f, L_H \) and \( L_L \). The land used to produce food and biofuels should be less than the total land available, \( L_f + L_H + L_L \leq L \). Without loss of generality, the output of food per unit of land is normalized to one, so \( L_f = f \). The high carbon biofuel is assumed to have a lower yield per unit of land than the low carbon biofuel (Khan and Crago, 2012). We use \( a_H \) and \( a_L \) to denote the amount of land required to produce one gallon of the high carbon and low carbon biofuel, respectively. Thus \( L_H = a_H e_H \) and \( L_L = a_L e_L \) with \( a_H > a_L \). The land availability constraint can be rewritten as \( f + a_H e_H + a_L e_L \leq L \).

The cost of producing biofuels and food consists of a constant per unit cost of industrial processing \( (c_H, c_L \) and \( c_f \) \) and an endogenously determined marginal cost of land. The per unit processing cost of the low carbon, less land-intensive biofuel is assumed to be higher than that of the other biofuel; thus, \( c_H < c_L \). The marginal cost of producing each of these, food and biofuels, is an increasing function of its production due to the increasing cost of diverting land from other uses. The gasoline supply curve is assumed to be upward-sloping and convex, denoted by \( c(g) \).

For the ease of illustration, the conceptual analysis considers a closed economy with a given supply of land and assumes that food production does not generate GHG emissions. In the numerical simulation we broaden the analysis to consider an open-economy with multiple commodity markets, various types of biofuels, a price elastic supply of land with heterogeneous quality and international trade in food, fuel and biofuel. The numerical analysis also includes markets for gasoline and diesel and accounts for GHG emissions from agricultural production. We now use this conceptual framework to analyze the mechanisms by which a carbon tax, a biofuel mandate and a LCFS policy affect food and fuel consumption and GHG emissions.

**Carbon tax**

With a GHG externality, whose marginal social damages are denoted by \( t \), the social planner determines the welfare-maximizing choices of fuels and food consumption by solving:

\[
\begin{align*}
\text{Max}_{g,t,e_H,e_L} & \int_0^m p_m(.)d(.) + \int_0^f p_f(.)d(.) - t(\delta g + \delta_H e_H + \delta_L e_L) - c(g) - c_H e_H - c_L e_L - c_f f \\
\text{subject to} & \quad m = r(g + \beta(e_H + e_L)) \quad \text{and} \quad f + a_H e_H + a_L e_L \leq L.
\end{align*}
\]

(1)

Substituting the VMT production function into the objective function we can write the Lagrangian of the resulting maximization problem as follows:

\[
L = \int_0^m p_m(.)d(.) + \int_0^f p_f(.)d(.) - t(\delta g + \delta_H e_H + \delta_L e_L) - c(g) - c_H e_H - c_L e_L - c_f f + \lambda (L-f-a_H e_H - a_L e_L)
\]

(2)

Assuming interior solutions of all decision variables exist, we obtain the following first order optimality conditions:

\[
r p_m(m) - \delta_t t - c'(g) = 0
\]

(3)

\[
r \beta p_m(m) - \delta_H t - c_H - a_H \lambda = 0
\]

(4)

\[
r \beta p_m(m) - \delta_L t - c_L - a_L \lambda = 0
\]

(5)

\[
p_f(f) - c_f - \lambda = 0
\]

(6)

where \( \lambda \) is the Lagrangian multiplier of the land constraint (a measure of the land rent). With a binding land availability constraint, \( \lambda \) is positive. Eqs. (3)–(5) state that the marginal benefits of consuming each type of fuel must equal its social marginal costs which include its marginal costs of production and marginal external costs of GHG emissions, represented by \( \delta g, \delta_H t \) and \( \delta_L t \), for gasoline, high carbon biofuel and low carbon biofuel, respectively. In a decentralized setting, if a fuel consumer has a choice of optimally selecting the level of consumption of gasoline and biofuels at given post-tax consumer prices \( p_g \) and \( p_f \) for gasoline and biofuel, respectively, then gasoline will be consumed such that \( p_g = r p_m \) and biofuel will be consumed such that \( p_f = r p_m \). This implies that with gasoline and biofuels being perfect substitutes in the production of miles they will be sold at an energy equivalent price \( \beta p_g = p_f \). Eq. (6) states that land is allocated to food production such that the price of the food crop is equal to its marginal cost of production including the processing cost \( c_f \) and the land rent \( \lambda \).

Eqs. (4) and (5) indicate that the mix of the two types of biofuels and the allocation of land between food and biofuels will be determined such that the marginal social cost of biofuel production, which includes marginal external cost of GHG emissions, per unit processing cost and the opportunity cost of land, is equated across the two types and can be represented by \( \delta_H t + c_H + a_H (p_f - c_f) = \delta_L t + c_L + a_L (p_f - c_f) \). As the carbon tax increases, the marginal cost of the high carbon biofuel...
increases more than that of the low carbon biofuel depending on their relative GHG intensities; this will lead to a switch toward the low carbon biofuel.

The effect of a carbon tax on the volume of biofuels consumed is, however, ambiguous. We illustrate this in the case with a single type of biofuel in Appendix 1 in the Supplementary Information (SI). We show that a carbon tax is likely to lead to an increase in biofuel consumption if the demand for VMT is inelastic and the supply of gasoline is elastic (Eq. (A1.3)). With an inelastic demand for VMT, the potential to reduce fuel consumption is low and the carbon tax is more likely to induce substitution toward low carbon fuels, particularly if their carbon intensity is relatively low. Moreover, if the supply of gasoline is elastic, a small change in relative prices of fuels due to the carbon tax will lead to a large increase in gasoline price and a relatively large substitution effect in favor of biofuels. The impact of the carbon tax on food prices will depend on the total volume and the mix of biofuels induced.

The carbon tax will unambiguously raise fuel price. By reducing the demand for gasoline, the carbon tax will reduce the marginal cost of gasoline and as a result the consumer price of gasoline will rise by less than the amount of the tax. However, the reduction in gasoline consumption will always be greater than the energy equivalent increase in biofuel consumption (because the carbon tax raises the cost of VMT and reduces VMT and total fuel consumption).

We refer to the ratio of the change in energy equivalent gasoline use to the energy equivalent increase in biofuel consumption due to the policy as the rebound effect and represent it by $\Delta e = \frac{\Delta g}{\beta \Delta e}$ where $\Delta g$ and $\Delta e$ represent policy-induced changes in biofuel and gasoline consumption, respectively. The rebound effect is negative (positive) if $\beta \Delta e < (>) \Delta g$. The rebound effect with a carbon tax is always negative; the negative effect is larger with a more elastic supply of gasoline, a more inelastic demand for food and a large $a_1$, which make it more costly to divert land from food to biofuel production.

\begin{equation}
L = \int_0^m p_m(x)dx + \int_0^1 p_f(x)dx - tZ - c_f tH - c_L tL - c_f f
\end{equation}

\begin{equation}
+ \lambda (L - f - a_H e_H a_L e_L) + \gamma (e_H + e_L - \theta g)
\end{equation}

With a biofuel mandate policy, the externality costs ($tZ$) are treated as a constant and are not internalized; hence they do not affect optimal decisions of food and fuel consumption. We obtain the following first order conditions (8)–(10) with condition (6) unchanged:

\begin{equation}
\frac{\partial L}{\partial p_m} = c_f (g) - \gamma \theta = 0
\end{equation}

\begin{equation}
\frac{\partial L}{\partial c_f} = c_H - a_H \lambda + \gamma = 0
\end{equation}

\begin{equation}
\frac{\partial L}{\partial c_L} = -a_L \lambda + \gamma = 0
\end{equation}

where $\lambda$ and $\gamma$ are the Lagrangian multipliers of the land constraint and the biofuel blend mandate, respectively. With binding land availability and biofuel blend mandate constraints, both $\lambda$ and $\gamma$ are positive. Eq. (8) indicates that the marginal benefit of gasoline ($\gamma p_m$) must equal the sum of its marginal cost ($c_f (g)$) and an implicit tax ($\gamma \theta$) on gasoline consumption. Eqs. (9) and (10) show that with a binding mandate the marginal benefit of biofuel consumption ($\gamma p_m$) is greater than the marginal cost of producing biofuels which consists of the processing cost of the feedstock ($c_f$ or $c_L$) and the opportunity cost of land which depends on the type of biofuel ($a_H \lambda$ or $a_L \lambda$). The gap between the marginal benefit and the marginal cost of biofuel production represents an implicit subsidy, $\gamma$, to induce biofuel consumption at the mandated level. These two equations also indicate that the implicit subsidy provided to biofuels is the same for both types of biofuels despite the difference in their GHG intensity and that the two biofuels will be consumed such that their marginal costs are equalized: $c_f tH + a_H \lambda = c_L tL + a_L \lambda$.

A marginal increase in the blend mandate will reduce food production and increase food prices depending on the extent to which it induces an increase in biofuel consumption, on the land requirement per gallon of biofuel and the slope of the demand curve of food. Eqs. (A2.3) and (A2.4) in the Appendix 1 in the SI show that the effect of an increase in the blend rate on food production is more negative if the land requirement per gallon of biofuel is high and the effect of the mandate on the volume of biofuel is high (this in turn increases with a more elastic demand for food, a less elastic supply of gasoline and a less elastic demand for miles).

5 The blend mandate could also be implemented as an explicit tax on gasoline and a subsidy on biofuels by the government.
The first order conditions indicate that the mandate leads to a transfer of surplus \((\rho t g)\) from gasoline producers to biofuel producers that is equivalent to \(\rho \left( e_H + e_L \right)\) and that fuel blenders earn zero profits since
\[
p_g g + p_e c - c' \left( g \right) g - (c_H + \alpha_H \lambda) e_H - (c_L + \alpha_L \lambda) e_L = 0
\]
with \(p_g = f p_m\) and \(p_e = \rho \beta p_m\).

Therefore, the cost of blended fuel to consumers would be a weighted average of the marginal costs of gasoline and biofuel. This is similar to the result obtained by de Gorter and Just (2009) and Lapan and Moschini (2012) who consider the case where consumers are sold a pre-blended fuel and blenders pass on the costs of biofuels to them by pricing the blended fuel at the weighted average of the marginal costs of blending gasoline and biofuels.

Like the carbon tax, the biofuel mandate reduces gasoline consumption by changing the relative prices of gasoline and biofuels in favor of biofuels. This will reduce the marginal cost (producer price) of gasoline. Its net impact on cost of VMT for consumers will depend on the extent to which the mandate raises the marginal cost of biofuels and lowers the marginal cost of gasoline. The reduction in the producer price of gasoline will reduce the extent to which biofuels displace gasoline. We show in Appendix 1 in the SI (Eq. (2.5)) that the rebound effect with a blend mandate could be positive (or negative) if the supply of gasoline is small (large) and the demand elasticity of food is high (low). With an inelastic demand for food, the mandate will lead to a larger increase in the marginal cost of biofuels and will result in a higher cost of VMT, a lower total fuel consumption and a smaller (or even negative) rebound effect than otherwise. The effect of the biofuel mandate on GHG emissions is also ambiguous (see Eq. (A.2.6) in the Appendix in the SI). It depends on the direct substitution effect of biofuels which increases as \(\delta_H\) and \(\delta_L\) become smaller relative to \(\delta_B\). It also depends on the indirect effect of biofuels on the demand for VMT due to the effect on fuel price, which in turn depends on the magnitudes of slopes of demand curves of VMT and food and the supply curve of gasoline; the mandate is likely to reduce emissions with an inelastic demand for food and VMT and elastic supply of gasoline.

**Low carbon fuel standard**

A LCFS requires the carbon intensity of the blended fuel to be less than a given level \(\sigma\) where \(\delta_H \leq \sigma \leq \delta_L\). The LCFS constraint can be written as: \(\delta_L g + \delta_H e_H + \delta_L e_L \leq \sigma (g + e_H + e_L)\). The social planner’s welfare-maximizing problem is now as follows:

\[
L = \int_{g}^{m} p_m(\cdot) d(\cdot) + \int_{0}^{f} p_f(\cdot) d(\cdot) - LZ - c(g) - c_H e_H - c_L e_L - c_f f \\
+ \lambda \left( L - f - \alpha_H e_H - \alpha_L e_L \right) + \rho \left( (g + e_H + e_L) - \delta_L g - \delta_H e_H - \delta_L e_L \right)
\]

where \(\mu \geq 0\) is the shadow value of the LCFS constraint and \(LZ\) is considered a constant term representing externality costs due to GHG emissions. This leads to first order conditions (13)-(15) with condition (6) unchanged:

\[
\rho p_m(\cdot) + \rho \left( (\sigma - \delta_L) - c \right) = 0
\]  

\[
\rho \beta p_m(\cdot) + \rho \left( (\sigma - \delta_H) - c_H \alpha_H \lambda \right) = 0
\]  

\[
\rho \beta p_m(\cdot) + \rho \left( (\sigma - \delta_L) - c_L - \alpha_L \lambda \right) = 0
\]

Since \(\delta_H \leq \sigma \leq \delta_L\), the LCFS constraint imposes an implicit tax on gasoline equal to \(\rho (\delta_L - \sigma)\) and provides implicit subsidies to high carbon and high carbon biofuels equal to \(\rho (\sigma - \delta_H)\) and \(\rho (\sigma - \delta_L)\), respectively. This makes it similar in spirit to a biofuel blend mandate discussed above, except that the magnitude of the implicit gasoline tax and biofuel subsidies depends not only on the stringency of the constraint, but also on the carbon intensity of gasoline and biofuels relative to each other and relative to the standard. As shown in Eqs. (14) and (15), the LCFS provides a higher implicit subsidy for biofuels with low carbon intensity since \(\delta_H > \delta_L\) and thus promotes the production of low carbon biofuels. Moreover, the LCFS differs from a carbon tax in that it imposes the implicit tax only on the portion of the carbon intensity of gasoline larger than the LCFS and it subsidizes biofuels instead of taxing them. If both the LCFS and the biofuel blend mandate yield the same level of biofuel production, the LCFS is likely to promote a larger share of cellulosic biofuels and thus have a less negative impact on food prices and a smaller ILUC effect.

A LCFS always reduces gasoline use like a biofuel blend mandate and a carbon tax. However, the rebound effect of a LCFS and its effect on GHG emissions are ambiguous as in the case of the blend mandate, as shown in the (Eq. (3.5)). The LCFS will lead to a negative rebound effect and reduce GHG emissions if the supply of gasoline is elastic and the demand for food is inelastic. An elastic supply of gasoline implies a large displacement effect of biofuel. On the other hand, the more inelastic the demand for food, the larger the increase in land rents and, therefore, in the marginal cost of producing biofuels. As the demand elasticity for food becomes smaller, it becomes more cost-effective to meet the LCFS by lowering \(g\) rather than increasing \(e\), thus leading to a larger negative rebound effect and reduction in GHG emissions than otherwise. The likelihood that the LCFS reduces GHG emissions also increases with an inelastic demand for VMT. In the event that the LCFS reduces the cost of VMT, an inelastic demand for VMT assures a small “VMT effect”. This is similar to the finding in Holland et al. (2009) except that we show how this ambiguity depends on demand and supply parameters in both food and fuel sectors.
Numerical model

We simulate the impacts of these policies by applying a multi-market, multi-period, price-endogenous, nonlinear mathematical programming model, BEPAM that integrates the agricultural and transportation fuel sectors in the US and incorporates international trade in agricultural commodities, fuel and biofuels with the ROW. Market equilibrium is achieved by maximizing the sum of consumers’ and producers’ surpluses in the agricultural and transportation fuel sectors subject to various material balance, technological and land availability constraints in a dynamic framework for the 2007–2030 time period. The demand for transportation fuels is driven by the demand for VMT that are produced by blending liquid fossil fuels and biofuels. The transportation sector includes markets for gasoline, diesel and several first- and second-generation biofuels. Biofuel production competes with food/feed production in the agricultural sector for agricultural resources, particularly land. To analyze the land use effects of biofuels, BEPAM includes markets for primary and processed crop commodities, livestock products, and cellulosic feedstocks consisting of crop and forest residues and perennial energy crops (switchgrass and miscanthus) for biofuel production.

The RFS and LCFS policies impose gradually increasing constraints that lead to an increasing demand for biofuels and therefore for land over time. These land use decisions are linked over time due to the perennial nature of energy crops whose productive lifetimes are estimated as 10 to 15 years and whose costs of production differ over their life-cycle which includes a one to two year establishment phase and then annual variable costs after that. Moreover, with a finite horizon considered in the model, the economic value of a standing perennial crop beyond the terminal year of the planning horizon (i.e., the present value of net returns after the terminal year until the productive life of the energy crop) needs to be taken into account when making production decisions. To address these issues, we use a ten-year rolling horizon approach to solve the model iteratively for each year of the 2007–2030 period. Specifically, in each iteration, starting in 2007, we assume that producers make resource allocation plans for the next ten years. After solving each 10-year market equilibrium problem we take the first-year’s solution values as ‘realized’, move the horizon one year forward and solve the new problem, and iterate until the problem is solved for year 2030 (thus, the last iteration considers the period 2030–2039). The policy targets for each year of the 10-year period in each iteration are specified exogenously. In each 10-year run, when determining the land allocation to perennials the planted acreage is initialized at the optimal values found in previous iterations, but conversion back to conventional crop production is allowed at a conversion cost.

This model determines several endogenous variables simultaneously, including VMT, fuel and biofuel consumption, imports of gasoline and sugarcane ethanol, mix of biofuels and regional land allocation among different food, feed and fuel crops and livestock over the given time horizon. We now briefly describe the key features and assumptions about transportation and agricultural sectors. The detailed algebraic structure of the model can be found in Appendix 2 in the SI. The GAMS code is available in Appendix 3 in the SI. The data and parametric assumptions are described in Appendix 4 in the SI.

Transportation fuel sector

BEPAM includes linear demand curves for VMT with four types of vehicles, including conventional gasoline, flex fuel, gasoline-hybrid, and diesel vehicles. The VMT production function considers the energy content of alternative fuels, fuel economy of each type of vehicle, the forthcoming Corporate Average Fuel Economy standards, and technological limits on blending fossil fuels and biofuels for each of these four types of vehicles, as specified by Energy Information Administration (EIA, 2010b). We exogenously shift demand curves for VMT with each type of vehicle over time as projected by the Annual Energy Outlook (EIA, 2010b) to capture the growth in demand due to changes in vehicle fleet, income and population.

We include linear supply curves for domestic gasoline and diesel as well as for gasoline supply and demand in the ROW. Exports of gasoline from the ROW to the US are determined by the difference between gasoline demand and supply in the ROW; diesel is assumed to be produced domestically. These supply curves are calibrated for 2007 using data on fuel consumption and production in the US and for the ROW (EIA, 2010a). The short-run supply elasticity of domestic gasoline in the US is based on Greene and Tishchishyna (2000) and is consistent with estimates reported by Gately (2004), Greene and Ahmad (2005) and Huntington (1991). The elasticity of demand for gasoline in the ROW is based on a review of the literature by Hamilton (2009) while the short-run price elasticity of supply of gasoline is based on the review of literature in Leiby (2008). Key assumptions about demand elasticity for VMT and supply elasticities of fuels are reported in Table A1 in Appendix 4 in the SI.

The biofuel sector includes several first- and second-generation biofuels. First-generation biofuels include domestically produced corn ethanol and imported sugarcane ethanol, soybean biodiesel, DDGS-derived corn oil and waste grease. Second-generation biofuels included here are cellulosic ethanol and BTL diesel produced using the Fischer–Tropsch process. BTL diesel is a drop-in fuel that can be blended with petroleum diesel without blending constraints and has similar energy properties to petroleum diesel. In contrast to the first generation biofuels, second generation biofuels such as BTL diesel do not compete with food production.

We choose this time period because it allows us to analyze the effects of the RFS from its year of establishment following the EISA in 2007. According to the Annual Energy Outlook (Greene and Ahmad, 2005), the RFS is unlikely to be met by 2022 as mandated by EISA but is likely to be met by 2030.

A detailed discussion of the numerical simulation model, including the algebraic form and computer codes can be found in the SI.
content. Cellulosic ethanol and BTL diesel are derived from cellulosic feedstocks, corn stover, wheat straw, forest residues, miscanthus and switchgrass.

The feedstock costs of biofuels consist of two components: a cost of producing the feedstock which includes costs of inputs and field operations, and a cost of land. The former are calculated at county level for each crop and aggregated to a crop reporting district (CRD) level using data and methods described in Khanna et al. (2011) while the costs of land are endogenously determined by the shadow price of the land constraint in the model. Technological parameters for converting feedstock to different types of biofuel and the industrial costs of processing feedstocks and producing biofuels are described in Chen et al. (2012). These costs are assumed to decline due to learning-by-doing as cumulative production increases using an experience curve approach represented by \( Y = aX^b \), where \( Y \) is the unit cost of production, \( X \) is the cumulative experience typically represented by cumulative production, \( a \) is the initial production cost of the first unit and \( b \) is a parametric constant capturing the rate of cost reduction. The learning rate, defined as \( 2^b \), is the rate at which per unit cost of a technology is expected to decline with every doubling of cumulative production. The parameters used to specify these experience curves for the four types of biofuels are shown in Table A2 in Appendix 4 in the SI. The conversion efficiencies (yield of biofuel per bushel or ton of feedstock) are exogenously fixed and based on the estimates in GREET 1.8c for corn ethanol and Humbird et al. (2011) for cellulosic ethanol.

**Agricultural sector**

The agricultural sector includes fifteen conventional crops, eight livestock products, two energy crops, crop residues from the production of corn and wheat, forest residues, various processed commodities, and co-products from the production of corn ethanol and soybean oil. In the crop and livestock markets, primary crop and livestock commodities are consumed either domestically or traded with the ROW (exported or imported). The primary crop commodities can also be processed or directly fed to various animal categories. Domestic and export demands and import supplies are incorporated by assuming linear price-responsive demand/supply functions. Elasticities used to calibrate domestic and export demand and import supply curves are reported in Appendix 4 in the SI. The commodity demand functions and export demand functions for tradable row crops and processed commodities are shifted upward over time at exogenously specified rates.

The model considers the 295 CRDs in 41 US states as spatial decision units and incorporates the heterogeneity in crop and livestock production across these CRDs. Production costs and yields of individual crop/livestock activities and resource endowments are specified differently for each CRD based on crop/livestock budgets reported by various agricultural experiment stations and the National Agricultural Statistics Service (NASS) database. Crops can be produced using alternative tillage, rotation, and irrigation practices. Crop yields increase over time at exogenously given rates based on econometrically estimated trends and price responsiveness of crop yields in the US (Khanna et al., 2011). Following Hertel et al. (2010), we assume that marginal lands have a crop productivity that is two thirds of the average cropland productivity.

Yields and costs of production of crop residues and dedicated energy crops also differ across regions. Corn stover and wheat straw yields for each CRD are obtained based on grain-to-residue ratio of dry matter of crop grain to dry matter of crop residues and the moisture content in the grain reported in Sheehan et al. (2003), Wilcke and Wyatt (2002) and Graham et al. (2007). Similar to Graham et al., 2007, we assume that 50% of the residue can be removed from fields if no-till or conservation tillage is practiced and 30% can be removed if till or conventional tillage is used. The costs of producing corn stover and wheat straw include the additional cost of fertilizer that needs to be applied to replace the loss of nutrients and soil organic matter due to the removal of the crop residues from the soil, and the costs of harvesting and storage. In the absence of observed yield data for energy crops, we use the simulated biomass yields obtained from MISCANMOD and calculate the costs of producing them over their lifetime (Jain et al., 2010). Yields and costs of production of the bioenergy crops are assumed to be the same on marginal lands and regular croplands, but they vary regionally. The model includes several types of land, namely regular cropland, idle land, cropland pasture, pasture land, and forestland pasture, for each CRD. Land under conventional crops in each CRD is assumed to change in response to crop prices, using estimated crop-specific price elasticities of acreage and price elasticity of total acreage. Idle land and cropland pasture are assumed to be available to be converted to conventional crop or energy crop production. Other land, including pasture land and forestland pasture are fixed at 2007 levels while land enrolled in the Conservation Reserve Program is fixed at levels authorized by the Farm Bill of 2008.

We use lifecycle analysis to estimate GHG intensity of each type of biofuel, which includes emissions generated during the process of crop production, transportation and conversion to liquid fuel as well as the soil carbon sequestered during the process of crop production. The agricultural phase of GHG emissions includes emissions from agricultural input uses such as fertilizer, chemicals, fuels and machinery. We obtain GHG emissions for biofuel conversion as well as its distribution and use from GREET 1.8c. We assume soil carbon under energy crops and conservation till will increase at a rate suggested in Adler et al. (2007) and Anderson-Teixeira et al. (2009). The collection of crop residues such as corn stover and wheat straw may lead to a loss of soil carbon (Anderson-Teixeira et al., 2009). Given the complexity of the issue involved and the difficulty in quantifying this soil carbon loss (EPA, 2010), we assume that the residue collection rates assumed here do not lead to a soil...
The estimated national average life-cycle GHG intensity of fuels is summarized in Table A3 in Appendix 4 in the SI. To examine the implications of biofuel production in the US on ILUC related emissions internationally we include an exogenously specified GHG intensity for each feedstock. These emissions intensities vary widely across studies (as reviewed in Khanna and Crago (2012)). Estimates assumed here are also reported in Table A3 in the SI based on EPA (2010).

Results

We first validate the simulation model for 2007 assuming existing fuel taxes, the corn ethanol mandate, ethanol tax credit and import tariffs on Brazilian sugarcane ethanol, and compare the model results with the corresponding observed values in 2007. The differences between model results and the observed land use allocations and commodity prices for major crops in the US (corn, soybeans, wheat, and sorghum) are typically less than 10% (see Table A4 in Appendix 4 in the SI). Fuel prices and consumption also deviate less than 10% from observed values.

Policy scenarios

We simulate a no-policy baseline (Business-as-Usual, BAU) scenario and three policy scenarios: a carbon tax, the RFS and a LCFS policy. The EISA, 2007 established the RFS which mandates the annual consumption of a specified minimum quantity of aggregate biofuel as well as minimum quantities of specific types of biofuels to be blended with fossil fuels for the period 2007–2022. The categories of biofuels included are corn ethanol, advanced biofuels (to be met by sugarcane ethanol and biodiesel) and cellulosic biofuels (consisting of cellulosic ethanol and BTL diesel). The USEPA implements the quantity mandate by determining a blend rate for biofuels with expected fossil fuel use such that the desired quantity of biofuel consumption will be achieved. The blend rate determines the obligations of fuel refiners and blenders, who are the responsible parties for meeting the mandate. Requirements for cellulosic biofuels for 2010–2013 have been waived due to the lack of commercial supply and the targets for cellulosic biofuels are unlikely to be achieved by 2022. We impose the annual volumetric targets for biofuels projected by the Annual Energy Outlook (AEO) (EIA, 2010b) as a mandate and refer to that as the RFS. Following the AEO projections (EIA, 2010b), we assume that cellulosic biofuel production commences in 2015. We impose a target of 39.4 Billion (B) ethanol equivalent gallons of biofuel in 2030 with an upper limit of 15 B gallons on corn ethanol. We then iteratively solve the model to find the annual blend rates that achieve the annual volumetric targets projected by the AEO. These blend rates are found to range from 6% in 2007 to 24.5% in 2030.11

To compare the effects of the RFS with the LCFS and carbon tax policies, we normalize the three policies to achieve the same domestic GHG emissions (from the transportation and agricultural sectors) as the RFS. The LCFS restricts the ratio of GHG emissions from all on-road transportation fuels blended/consumed in a given year to the total energy produced by all those fuels in that year to be below an exogenously specified intensity level for that year. The LCFS is assumed to be binding only at the aggregate level and not the firm level; it thereby implicitly allows for the possibility of trading among fuel providers, some of whom might over-achieve the LCFS while others may under-achieve it, the industry as a whole meets the LCFS cost-effectively. It also allows trading in carbon intensity reductions across biofuels, gasoline and diesel. We assume that the LCFS is implemented starting in 2015 to synchronize it with the availability of cellulosic biofuels. We find that an LCFS that sets annual targets for lowering the GHG intensity of fuel that linearly increase to 8% by 2030 relative to the GHG intensity of conventional gasoline and petro-diesel in 2005 would achieve the same level of cumulative domestic GHG emissions reduction as the RFS. We also find that a carbon price of $52 per ton of CO₂ equivalent imposed over the 2007–2030 period would lead to the same level of domestic GHG emissions as the RFS. Lastly we examine the implications of supplementing the RFS with a carbon tax or a LCFS and a scenario with the three policies implemented together.

Effects of biofuel and climate policies on the fuel sector

Mix of biofuels: the three policies differ in the extent to which they induce biofuel production, types of biofuels produced and the reduction in fossil fuel consumption. The cumulative volume of biofuels induced under the RFS, LCFS and carbon tax policies are 545 B gallons, 342 B gallons and 118 B gallons, respectively (see Table 1). As compared to the BAU scenario, the RFS leads to an almost four-fold increase in cumulative biofuel production and 71% of the biofuels produced are first-generation biofuels (including corn ethanol, sugarcane ethanol and biodiesel derived from vegetable oils); in comparison the carbon tax induces only a marginal increase in first-generation biofuel production and is not large enough to induce any second-generation biofuel. The LCFS induces a doubling in cumulative biofuel production relative to the BAU scenario and about 76% is in the form of second-generation biofuels; the share of corn ethanol is substantially smaller than under the RFS. The LCFS also differs from the RFS in that it induces a much larger share of cellulosic biofuels from less carbon intensive energy crops, like miscanthus, than from crop and forest residues (see Fig. 1(a)).

Fuel prices and consumption: the carbon tax of $52 per ton of CO₂ translates into a tax of $0.61 per gallon on gasoline, $0.70 per gallon on diesel, $0.19 per gallon on corn ethanol, and $0.10 per gallon on sugarcane ethanol in 2030 (see Fig. 1(b)). The corresponding tax on cellulosic biofuels would be close to zero, due to their low carbon intensities. By reducing the

11 Blend rates after 2030 are assumed to be the same as that in 2030 for setting terminal conditions in the model.
Effects of climate and biofuel policies on fuel mix, consumption and GHG emissions.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>BAU</th>
<th>Carbon tax</th>
<th>RFS</th>
<th>LCFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative fuel consumption, 2007–2030 (Billion gallons)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US gas consumption</td>
<td>3155.1</td>
<td>3056.0</td>
<td>2898.6</td>
<td>3024.3</td>
</tr>
<tr>
<td>US gasoline imports</td>
<td>2031.2</td>
<td>1949.6</td>
<td>1821.5</td>
<td>1923.3</td>
</tr>
<tr>
<td>US petro-diesel consumption</td>
<td>989.2</td>
<td>954.7</td>
<td>969.3</td>
<td>980.1</td>
</tr>
<tr>
<td>ROW gas consumption</td>
<td>4421.0</td>
<td>4467.5</td>
<td>4532.9</td>
<td>4477.8</td>
</tr>
<tr>
<td>First generation biofuels</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol share in gasoline blends</td>
<td>3.5</td>
<td>3.8</td>
<td>25.3</td>
<td>21.9</td>
</tr>
<tr>
<td>Biodiesel share in diesel blends</td>
<td>0.4</td>
<td>0.6</td>
<td>1.9</td>
<td>2.7</td>
</tr>
<tr>
<td>Domestic gas consumption</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Domestic diesel market</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Domestic gasoline market</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global gasoline market</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Reduction in cumulative GHG emissions relative to baseline, 2007–2030 (Billion tons) | | | | |
| US GHG emissions | | | | |
| Global GHG emissions | | | | |
| Vehicle mile consumption in 2030 (Billion miles) | | | | |
| Gas blend VMT | 4119.6 | 4023.7 | 4177.2 | 4164.7 |
| Diesel blend VMT | 449.0 | 437.7 | 444.9 | 450.0 |
| Biofuel share and rebound effects in 2030 (%) | | | | |
| Ethanol share in gasoline blends | 3.5 | 3.8 | 25.3 | 21.9 |
| Biodiesel share in diesel blends | 0.4 | 0.6 | 1.9 | 2.7 |
| Domestic gas consumption | | | | |
| Domestic diesel market | | | | |
| Global gasoline market | | | | |

a Numbers in the parentheses represent the percentage changes in fuel consumption and GHG emissions under each policy relative to the no-policy baseline scenario. The change in global GHG emissions is estimated after including the ILUC effect in the BAU and in the policy scenarios and net of the global rebound effect. US GHG emissions over the period 2007–2030 are 52.3 Billion tons under the BAU scenario.
b Includes biodiesel from various vegetable oils in ethanol energy equivalent gallons.
c Ethanol energy equivalent gallons.
d A carbon tax always leads to negative rebound effects in the fuel markets.

The implicit tax on gasoline and diesel under the RFS is $0.28 per gallon on gasoline and diesel. Unlike the carbon tax, the RFS induces the mandated level of advanced and cellulosic biofuel production by providing large implicit subsidies. In 2030, these are $0.89 per gallon on sugarcane and cellulosic ethanol and limited to $0.49 per gallon on corn ethanol due to the cap on corn ethanol production at 15 B gallons. The reduction in gasoline imports due to the RFS-induced biofuel production leads to a 12% reduction in the world price of gasoline compared to the BAU scenario. Hence, despite the implicit tax on gasoline, we find the consumer price of gasoline blend in the US would be 4% lower than the price of gasoline in the BAU scenario in 2030 (see Fig. 1(c)). The producer price of diesel decreases much less (by 3%) and hence the consumer price of diesel blend is 4% higher than in the baseline scenario in 2030.

Under the LCFS the implicit subsidies and taxes depend not only on the stringency of the LCFS constraint, but also on the carbon intensity of fuels as shown in Fig. 1(b). In 2030, these subsidies are $0.41 and $0.60 per gallon for corn and sugarcane ethanol, respectively. The subsidies for cellulosic ethanol (particularly from miscanthus) and BTL diesel are significantly larger, due to their lower carbon intensity, and differ by the feedstock used. For the major cellulosic feedstocks these implicit subsidies range from $0.73 to $1.31 per gallon. This is a key difference between the incentives provided by the LCFS and RFS for different types of biofuels and it explains the differential mix of biofuels induced by the two policies as well as the differential effect of these policies on food prices in Fig. 1(d). The LCFS also imposes a tax of $0.16 per gallon on gasoline and $0.22 per gallon on diesel in 2030. The reductions in the consumer price of gasoline and diesel under the LCFS are similar to those under the RFS.

As a result of the large increase in domestic fuel price, the carbon tax has a very large negative domestic and global rebound effect. Domestic gasoline consumption decreases by 16 times more than the increase in biofuel consumption in the US. Even though gasoline consumption increases slightly in the ROW due to the small reduction in world price of gasoline, the decrease in global gasoline consumption is three times larger than the increase in biofuel consumption in the US. On the other hand, the RFS leads to positive rebound effects of 9% and 54% on domestic and global gasoline consumption in 2030, respectively; implying that a gallon of ethanol displaces 0.91 and 0.46 gallons of energy equivalent gasoline in the domestic and global markets, respectively. The corresponding rebound effects on domestic and global gasoline markets under the LCFS are positive and marginally smaller than those under the RFS (8% and 50%, respectively). Despite the positive rebound effect.
effect in the domestic gasoline market, the RFS reduces cumulative gasoline imports by 10% (over 2007–2030), due to the large volume of ethanol induced. The LCFS and carbon tax reduce gasoline imports by 5% and 4%, respectively. Thus, the RFS would outperform the other policies in meeting energy security objectives.

Effects of biofuel and climate policies on the agricultural sector

Land use: the three policies differ in their intensive and extensive margin effects of land use. Since the LCFS induces the largest amount of energy crop production, it expands total actively farmed cropland by 6% as compared to the BAU scenario. The RFS leads to an increase in total cropland by 2%, while the carbon tax leads to very marginal changes in land use (see Table 2). The RFS increases land under corn by 26% relative to the BAU and diverts 32% of the land for ethanol production. The RFS induces energy crop production on 4.9 M acres, of which about 3.7 M acres are diverted from marginal lands due to their lower opportunity cost, and the rest will come from the reduction in land previously under other food crops. It also induces harvesting of corn stover on 74% of corn acres. The increase in demand for land for biofuel reduces the land under corn for food and other food crops by 5% and 7%, respectively, compared to BAU scenario.

The larger amount of second-generation biofuel production under the LCFS induces much greater land under energy crops (30.4 M acres) than that under the RFS but smaller acreage (50.9 M acres) of land from which corn and wheat residues will be harvested. Of the total land under energy crops, more than 50% (15.8 M acres) will be converted from cropland pasture (which increases the total cropland to 311.8 M acres) while the rest (14.6 M acres) will be diverted from the land previously under food crops. Due to reduced reliance on corn ethanol to meet the LCFS requirement, the gross amount of land diverted for corn ethanol production under the LCFS would be 53% (6.2 M acres) smaller in 2030 as compared to the RFS while land under corn production (for food) will be higher than under the RFS.

Food prices: all three policies raise food crop prices by converting land from food crops to biofuel crops and increasing land rents. However these effects differ due to the difference in the mix of biofuels induced. The carbon tax generates modest impacts on food prices with the corn price increasing by 6% relative to the BAU scenario (see Fig. 1(d)), in part due to the increase in corn ethanol consumption and in part due to higher carbon inputs in corn production. Among the policies
considered here, the RFS raises food prices the most due to the large first-generation biofuels production. Corn and soybean prices would be 33% and 25% higher in 2030, respectively, compared to the BAU scenario. The LCFS would lead to a much smaller increase in crop prices than the RFS with corn and soybean prices being 18% and 10% higher than in the BAU scenario. Due to the greater energy crop production under the LCFS, biomass price under the LCFS will be $69 per ton in 2030, which is 4% higher than that under the RFS alone.

Effects of biofuel and climate policies on GHG emissions and social welfare

**Global GHG emissions:** although the three policies are designed to reduce cumulative domestic GHG emissions over the 2007–2030 period relative to the BAU scenario, they differ in the mechanisms by which they achieve that reduction and in the impact on global GHG emissions. While the RFS and LCFS achieve emissions reductions by displacing fossil fuels with biofuels, the carbon tax reduces emissions by reducing VMT. As shown in Table 1, the carbon tax reduces VMT with gasoline and diesel blends by 2.3% and 2.5%, respectively, while the RFS and LCFS increases VMT with gas blend in 2030 by 1.4% and 1.1%, relative to the BAU levels.

These policies also differ in their impact on global GHG emissions due to the differences in ILUC-related emissions and the effect on ROW gasoline consumption. The large reduction in gasoline imports under the RFS leads to a larger reduction in global gasoline price, which increases cumulative ROW gasoline consumption by 2.5% as compared to about 1% under the LCFS and carbon tax policies (see Table 1). Therefore, the carbon tax leads to the largest reduction in global emissions by 3.1% relative to the BAU scenario, while the reductions under the RFS and LCFS are 0.4% and 2.6%, respectively. Our results differ from Drabik and de Gorter (2011) and Bento et al. (forthcoming) that find that the corn ethanol mandate is likely to increase global GHG emissions while decreasing domestic emissions. This is in part due to the inclusion of advanced biofuels here which results in a larger decrease in domestic emissions intensity that offsets the increase in emissions in the ROW.

**Social welfare:** we compute domestic social welfare as the sum of discounted consumers’ and producers’ surpluses in US agricultural and transportation fuel sectors and government revenue from fuel/carbon taxes net of the externality costs due to GHG emissions over the period 2007–2030. Externality costs are valued at the carbon price of $52 per ton of CO₂ equivalent. We assume an annual discount rate of 4%. Based on the changes in prices and quantities of tradable commodities, we also compute the change in social welfare in ROW agricultural and fuel sectors relative to the no-policy baseline. By improving the terms-of-trade for the US, all three policies increase US economic surplus (without considering externality costs of GHG emissions) relative to the no-policy baseline scenario. The carbon tax leads to the largest gain in US economic surplus by $134 B (and in government revenue)12, followed by the RFS and LCFS by $47 B and $33 B, respectively. As a percentage of the US social welfare in the no-policy baseline scenario, these gains, however, are modest even with the consideration of externality costs and range from 0.3% under the LCFS to 0.8% under the carbon tax policy.

By increasing food prices and reducing gasoline imports, these policies would reduce economic surplus in the ROW, with the loss being largest ($324 B) under the RFS since it raises food prices and reduces gasoline imports the most across the three policies. Even after including the benefits of reducing GHG emissions, the RFS would lead to a net reduction in global social welfare by 1.0% as a percentage of the BAU US social welfare. The corresponding reduction under the LCFS is more modest (0.2%). In contrast, the carbon tax policy in the US would result in a small but positive increase in global social welfare (see last row of Table 3).

These policies also differ in their distributional effects on fuel and food consumers’ and producers’ surpluses in the US and ROW. By increasing consumer prices of fuels, the carbon tax reduces US fuel consumers’ surplus by $1378 B relative to the BAU scenario. In contrast, the RFS and the LCFS increase US fuel consumers’ surplus by $43 B and $90 B, respectively. US fuel

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12 These findings are similar to those obtained by Lapan and Moschini (2012) and Chakravorty and Hubert (2013).
Table 3
Effect of climate and biofuel policies on social welfare relative to the baseline scenario over 2007–2030 ($ Billion)*.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Carbon tax</th>
<th>RFS</th>
<th>LCFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>US fuel consumers (a)</td>
<td>–1377.9</td>
<td>42.7</td>
<td>89.6</td>
</tr>
<tr>
<td>US fuel producers (b)</td>
<td>–164.9</td>
<td>–203.5</td>
<td>–87.3</td>
</tr>
<tr>
<td>US agricultural consumers (c)</td>
<td>–12.9</td>
<td>–124.0</td>
<td>3.7</td>
</tr>
<tr>
<td>US agricultural producers (d)</td>
<td>19.6</td>
<td>296.6</td>
<td>10.9</td>
</tr>
<tr>
<td>US government (e)</td>
<td>1669.8</td>
<td>35.0</td>
<td>16.4</td>
</tr>
<tr>
<td>Reduction in US externality costs (f)*</td>
<td>75.1</td>
<td>63.4</td>
<td>58.5</td>
</tr>
<tr>
<td>US economic surplus (a+b+c+d+e)</td>
<td>133.7</td>
<td>46.7</td>
<td>33.4</td>
</tr>
<tr>
<td>US social welfare (a+f)</td>
<td>208.9 (0.8)</td>
<td>110.1 (0.4)</td>
<td>91.9 (0.3)</td>
</tr>
<tr>
<td>ROW agricultural consumers and producers (g)</td>
<td>–10.4</td>
<td>–96.8</td>
<td>–6.1</td>
</tr>
<tr>
<td>ROW gasoline consumers and producers (h)</td>
<td>–127.9</td>
<td>–249.2</td>
<td>–106.5</td>
</tr>
<tr>
<td>Sugarcane ethanol consumers and producers (i)</td>
<td>1.5</td>
<td>21.9</td>
<td>1.1</td>
</tr>
<tr>
<td>ROW/ economic surplus (j)</td>
<td>–136.9</td>
<td>–324.1</td>
<td>–111.5</td>
</tr>
<tr>
<td>Reduction in global externality costs (k)*</td>
<td>56.1</td>
<td>2.4</td>
<td>36.5</td>
</tr>
<tr>
<td>World social welfare (a+j+k)</td>
<td>53.0 (0.2)</td>
<td>–274.9 (–1.0)</td>
<td>–41.6 (–0.2)</td>
</tr>
</tbody>
</table>

* Numbers in the parentheses represent the percentage change in social welfare under each policy relative to US social welfare under the no-policy baseline scenario.

Environmental externality costs are valued at a carbon price of $52 per MT of CO2 equivalent and discounted over the period 2007–2030.

We now consider the welfare and GHG effects of supplementing the existing RFS with varying combinations of the carbon tax and LCFS policies considered above. The effects of combining the RFS with the LCFS on the mix of biofuels and food and fuel production are similar to those under the RFS alone since the blend mandate is a binding constraint. However, the addition of a carbon tax to the RFS leads to a reduction in total biofuel production (by 3%) and a shift in the mix of biofuels towards second-generation biofuels (Fig. 2(a)). It increases corn price by 6% due to the high cost of fertilizer for corn production in 2030 (Fig. 2(b)) and leads to a higher reduction in gasoline imports (by 3%) and global GHG emissions (by 4%) than the RFS alone (Fig. 2(c)). By reducing externality costs due to GHG emissions, the addition of the carbon tax to the RFS further increases US and global social welfare relative to the RFS alone (see Fig. 2(d)), although percentage effects are fairly modest. The implementation of all three policies together results in marginally higher reduction in GHG emissions and higher domestic and global social welfare relative to the RFS alone because of reduced externality costs.

**Sensitivity analysis**

**Behavioral parameters in agricultural and fuel sectors**

We now examine the sensitivity of our results to variations in the parametric assumptions analyzed in the conceptual framework. In scenario (1), we double the demand elasticity of VMT from –0.2 to –0.4 while in scenario (2) we increase the ROW supply elasticity of gasoline from 0.2 to 0.4. In scenario (3), we consider a case with 100% higher export demand elasticities for food in the ROW relative to the benchmark case to examine the effect of the improvement in terms-of-trade on US social welfare. We keep the carbon tax rate and the LCFS at the same levels as in the benchmark scenarios to test sensitivity to one parametric change at a time.

We find that a small increase in the demand elasticity of VMT in scenario (1) leads to greater reductions in fossil fuel consumption and global GHG emissions than those with benchmark parameters under the carbon tax, while effects are negligible under the RFS and LCFS policies. In scenario (2) with an elastic ROW gasoline supply curve, these biofuel and climate policies achieve larger reductions in US gasoline consumption and imports as well as global GHG emission than benchmark results. An elastic gasoline supply also reduces the rebound effect across all the biofuel policies. In scenario (3),

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13 There is a small increase in producers’ surplus of Brazil’s sugarcane ethanol industry due to increased exports of ethanol to the US.
higher export demand elasticities for food in the ROW reduce the gain in US surplus due to terms-of-trade effect. In general, our results are robust and insensitive to the wide variations in these parametric assumptions.

Next, we compare the effects of parametric changes on the relative performance of alternative policies. Across the parameter assumptions considered here, the reduction in cumulative fossil fuel consumption (including gasoline and diesel) is largest under the RFS (by 7%) relative to no-policy baseline scenarios and smallest under the carbon tax (except when the demand elasticity of VMT is high, where the reduction in fossil fuel consumption is by 6%). The RFS also leads to the largest cumulative biofuel consumption between 544–547 B gallons, followed by the LCFS (335–343 B gallons) and the carbon tax (111–115 B gallons) under all parametric assumptions considered here. These results are not shown for brevity.

All three policies considered here raise food commodity prices in 2030 with the RFS having the largest negative impacts relative to the corresponding baseline levels and the carbon tax having the smallest effects (see Fig. 3(a)). The impact on crop prices, under all policies, is smaller when the demand for food is more elastic. Domestic and global rebound effects in the gasoline markets are lower under the LCFS (ranging between 4–8% and 36–51%, respectively) than under the RFS (5–11% and 41–55%, respectively) under all parametric assumptions considered here (Fig. 3(b)). The carbon tax policy yields the largest reduction in aggregate global GHG emissions (by 3.1–4.8%) compared to the no-policy level (see Fig. 3(c)), while the RFS leads to the smallest reduction in global GHG emissions (by 0.4–1.3%) among the three policies considered here due to the larger global rebound in the fuel market and ILUC-related emissions.

All three policies result in higher domestic social welfare as compared to the BAU under the various parametric assumptions considered here except in the case of the RFS under the high supply elasticity of gasoline scenario; in this case the economic gain due to the reduction in imported fuel becomes smaller than otherwise. We also find that the carbon tax always increases global social welfare after including externality costs. In contrast, the RFS and LCFS reduce global social welfare due to the efficiency costs imposed by these policies with the loss being largest under the RFS. Across the wide range of assumptions considered here, the impacts on US and world social welfare of these policies are modest (less than 2%) across all scenarios relative to the no-policy baseline levels (see Fig. 3(d)).

Learning-by-doing

The results presented above assumed that the unit processing costs of biofuels decline over time due to technological learning. We now examine the sensitivity of our results to this assumption by comparing them to the case where there is no reduction in the per unit processing costs of biofuels over the period 2007–2030. The absence of technological learning in biofuel sectors will not affect the mix and volume of biofuels under the RFS (assuming the nested constraints for different types of biofuels are binding) but will result in higher costs of blended fuel which in turn leads to a smaller total fuel consumption and a greater reduction in GHG emissions compared to the RFS with learning-by-doing. Under the LCFS, the absence of learning-by-doing increases reliance on first-generation biofuels by 64% and results in higher food prices and a smaller reduction in global GHG emissions. Under both policies, this leads to higher costs of biofuels, while reducing the
Conclusions

Fuel standards are being promoted by policy makers as a mechanism for reducing the dependence on fossil fuels imports and reducing GHG emissions from the transportation sector. We present both a conceptual framework and a numerical simulation model to examine the performance of two types of fuel standards (RFS and LCFS) and to compare these to the effects of a carbon tax policy. The conceptual analysis shows that in a closed economy with no leakage effects on the ROW, a carbon tax has an ambiguous impact on biofuel consumption but always reduces GHG emissions. The RFS and LCFS promote biofuel consumption but are likely to lead to a different mix of biofuels due to the difference in incentives provided for biofuels. Both policies reduce gasoline consumption but have ambiguous impacts on GHG emissions. By promoting biofuels, the RFS and the LCFS will divert land from food production and increase food prices, although to varying extents depending on the mix and volume of biofuels induced.

Our numerical simulation quantifies the effects of these policies on fuel mix, food and fuel prices, land use, and GHG emissions in an open economy for the US and the ROW. We also examine the social welfare and distributional effects of these policies for the US and the ROW. The three policies differ greatly in the cumulative volume and mix of biofuels induced. The RFS leads to an almost four-fold increase in biofuel production relative to a no-policy baseline scenario with a large reliance on first-generation biofuels; in comparison the carbon tax induces only a marginal increase in first-generation biofuel production and is not large enough to induce any second-generation biofuel production. The LCFS leads to a doubling of biofuel production relative to the BAU, but relies more on second-generation biofuels derived from low carbon-intensive energy crops and a low share of crop and forest residues. All three policies raise food crop prices by converting agricultural land from food crops to biofuel crops and increasing land rents; this increase is largest under the RFS and fairly modest with the carbon tax and the LCFS.

We also find that the RFS leads to a larger reduction in US gasoline consumption than the LCFS policy and the carbon tax policy. However, the LCFS and carbon tax policies considered here achieve a larger reduction in global GHG emissions although for different reasons. The larger share of second-generation biofuels under the LCFS than under the RFS or carbon tax policy has a higher direct displacement effect on GHG emissions. The LCFS also leads to smaller domestic and global
rebound effects and a smaller ILUC effect than the RFS. A carbon tax reduces GHG emissions primarily by reducing VMT and total fuel consumption.

By improving the terms-of-trade for the US, all three policies considered here increase US economic surplus. The gain is the largest under the carbon tax and smallest under the LCFS policy without considering the benefits from the GHG mitigation. By increasing food prices and reducing gasoline imports, these policies would reduce economic surplus in the ROW, with the loss being largest under the RFS since it raises food prices and reduces gasoline imports the most across the three policies. Even after including the benefits of reducing GHG emissions, the RFS and LCFS would lead to a net reduction in global social welfare. In contrast, the carbon tax policy in the US would result in a small but positive increase in global social welfare.

The sensitivity analysis shows that in two extreme cases with very elastic supply curve of gasoline or highly elastic export demand curves for crops the improvement in terms-of-trade and thus in domestic surplus would be smaller, though still positive, relative to the benchmark results. Our analysis did not consider other factors that could affect the terms-of-trade effect of biofuels, for example shifts in the export demand curves for crops that might occur due to improvements in crop production technology in the rest of the world in response to the biofuel-induced increases in crop prices. The impact of reduced demand for gasoline in the US on world gasoline prices could also be affected by the strategic behavior of OPEC in response to the large-scale biofuel production in the US which may cause them to reduce oil production (Hochman et al., 2011).

On the other hand, inter-temporal optimization by oil resource owners could lead to an increase in oil production in anticipation of the declining value of oil stocks due to biofuels (Quentin Grafton et al., 2012). Analysis of these effects on the welfare costs of the policies considered here is left for future research.

Appendix A. Supplementary Information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jeem.2013.09.006.

References


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