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The Market-Mediated Effects of Low Carbon Fuel Policies

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This article analyzes the domestic and global rebound effects of a carbon price policy, the existing Renewable Fuels Standard (RFS), and a proposed national Low Carbon Fuel Standard (LCFS) and examines implications for the greenhouse gas (GHG) mitigation benefits of these policies. This study shows that unlike a carbon price policy, the RFS generates positive domestic and global rebound effects, while the rebound effects under the LCFS may be positive or negative depending on the stringency of the LCFS target. The numerical simulation shows that a 10% LCFS generates a smaller positive rebound effect than the RFS, and that the rebound effect has a larger potential to offset the direct GHG savings resulting from the displacement of fossil fuels achieved by these policies compared to the indirect-land-use change effect. Nevertheless, all three policies reduce GHG emissions relative to a no-policy, business-as-usual scenario, with the RFS leading to a lower reduction in GHG emissions than the LCFS and the carbon tax.

Key words: biofuel mandate, carbon tax, dynamic optimization, greenhouse gas emissions, low carbon fuel standard, rebound effect, renewable fuel standard, second-generation biofuels.

Introduction

The transportation sector in the United States accounted for 29% of US total energy consumption and greenhouse gas (GHG) emissions in 2007, with only 2% of fuel consumption derived from renewable sources in 2007. Biofuels are being promoted to increase energy security and reduce GHG emissions through policies that establish mandates for blending biofuels with liquid fossil fuels and by setting standards for the reduction in the GHG intensity of transportation fuel. The Renewable Fuel Standard (RFS) established by the Energy Independence and Security Act (EISA) of 2007, sets quantity mandates for blending specific types of biofuels (based on their life-cycle GHG intensity) with fossil fuels. Although not initiated as a low-carbon fuel policy, it does seek to promote low carbon advanced biofuels and mitigate GHG emissions. It requires blending at least 136 billion (B) liters of biofuels (ethanol energy equivalence) with liquid fossil fuels by 2022; this would represent a five-fold increase in US biofuel consumption compared to that in 2007. A low carbon fuel standard (LCFS) requiring a 10% reduction in GHG intensity of transportation fuels by 2020 is being implemented in California (California Air Resources Board [CARB], 2009), and is being considered by several other states and at the national level. In contrast to these policies that indirectly seek to reduce GHG emissions, a carbon price policy could be established to create direct incentives to substitute low carbon fuels for fossil fuels.

Biofuels can affect GHG emissions in three ways. First, they can displace an energy-equivalent amount of fossil fuels; second, they can affect fossil fuel consumption by affecting fuel price; and third, they can have an indirect effect on land use, which results in a release of carbon stored in soils and vegetation. The first (displacement) effect directly reduces GHG emissions by substituting energy-equivalent amount of biofuels for fossil fuels. The second (rebound or market-mediated) effect arises because any unilateral low-carbon policy that reduces demand for fossil fuels by a large country such as the United States will lead to a reduction in the demand for oil in the world oil market and, thus, global fuel prices.[1] The third indirect land use change (ILUC) effect is caused by the adverse effect of biofuels production on food prices and resulting expansion of cropland on carbon-rich non-agricultural land in the rest of the world (ROW; see Khanna & Crago, forthcoming; Khanna, Crago, & Black, 2011).

While current biofuel production in the United States has relied primarily on corn as the feedstock, the

1. *Empirical estimates indicate that ethanol production in the United States has effectively reduced the average wholesale gasoline price by 5-10% compared to the case that would have been otherwise (Du & Hayes, 2009).*

goal of the RFS and other low-carbon fuel policies is to promote a mix of biofuels with a greater emphasis on biofuels produced from non-food crop based cellulosic feedstocks in the future. As compared to corn ethanol, these cellulosic biofuels have significantly lower GHG intensity, higher fuel yields per unit land, and they can be grown on low quality land or produced from crop or forest residues, thus mitigating the food vs. fuel competition for land. Thus, the displacement effect of biofuels and the ILUC effect on GHG emissions will depend not only on the volume of biofuels but also the mix of biofuels and their estimated ILUC effect.

The effect of biofuels on global fossil fuel price will depend, among other things, on the price responsiveness of fuel supply and the elasticity of demand for transportation fuel domestically and in the ROW.[2] While the biofuel-induced decrease in the fossil fuel price will always lead fuel consumption in the ROW to rebound positively (as in Bento, Klotz, & Landry, 2011; Rajagopal, Hochman, & Zilberman, 2011), its effect on domestic fossil fuel consumption will depend on the biofuel policies and the fuel pricing structure implemented in the United States. Several studies have analyzed the rebound effect of the RFS implemented as a blend mandate (requiring fuel producers to sell a specified blend of biofuels and gasoline) ranging from 7.5-12% over the 2009-2020 period (Bento et al., 2011; Drabik & de Gorter, 2011; Rajagopal et al., 2011; Thompson, Whistance, & Meyer, 2011).These studies also assume that fuel consumers are restricted to purchasing a pre-blended fuel (up to 10%), and fuel blenders will price the blended fuel as a weighted average of the prices of the two fuels. The domestic rebound effect under such a policy could be positive or negative for two reasons. First, a blend mandate can be met by reducing gasoline consumption and/or increasing biofuel consumption; this could create incentives to reduce gasoline consumption more than the increase in biofuel consumption.[3] Second, the consumer price of the blended fuel under the mandate could be higher or lower than that in the absence of the mandate, since the mandate will lower fossil fuel price while requiring the blending of high-cost biofuels. The studies above (with the exception of Thompson et al., 2011) find that the domestic rebound effect of a mandate is negative and ranges from (-)43% to (-)170%.

The provision of a pre-blended fuel priced at the weighted average price of gasoline and biofuel is feasible in the near term with blend rates up to 10% that are compatible with the existing vehicle technology. However, it is unlikely to be fully feasible in the long run considered here (up to 2030) when higher blend rates will be required to consume the mandated biofuel quantities and necessitate the significant adoption of flex-fuel vehicles. With a mix of conventional and flex-fuel cars, the government could impose a low blend requirement of 10-15% for all fuel consumers while allowing a choice about additional biofuel consumption (100% ethanol or hydrous ethanol), as is the case in Brazil currently. For simplicity we assume that all fuel consumers have a choice of the blend to consume and that biofuels are priced based on their energy content in order to induce consumption. Consequently, our estimates of the GHG savings due to biofuel polices should be considered as conservative since any pre-blending of fuels will result in a higher fuel price for domestic consumers and a smaller domestic rebound effect than with energy-equivalent pricing.

The purpose of this article is to examine the effects of the RFS modeled as a quantity mandate for biofuels for fuel prices and GHG emissions and to compare these to those of other low-carbon fuel policies (a national LCFS and a carbon price policy). We present a conceptual framework of the fuel sector to analyze the mechanisms by which alternative policies differ in their effects on fuel prices and fuel consumption and to identify the determinants of the rebound effect. We consider not only direct emissions savings due to the displacement of fossil fuels with biofuels, but also the market-mediated effect on GHG emissions arising due to the effect of bio-

2. *This effect will also depend on the strategic response by OPEC to the emergence of a renewable substitute for oil which could moderate or exacerbate the effect of biofuel production in a competitive fuel market. There are several views in the literature on ways to represent OPEC's behavior: as a profit-maximizing cartel, as a dominant firm with a competitive fringe, or as a social club operating competitively (Carlton & Perloff, 2000). Hochman, Rajagopal, & Zilberman, (2010) show that if OPEC behaves as a dominant firm treating the biofuel industry as a competitive fringe then the extent to which biofuel production in the United States will lower global fuel prices is smaller than if the world oil market is assumed to behave competitively. On the other hand, Sinn (2008) argues that the emergence of biofuels will accelerate extraction of fossil fuels, as the anticipation of declining value of their stocks motivates fossil fuel owners to deplete their stocks more rapidly.*

3. *A blend mandate is similar in spirit to the LCFS in that it also imposes an implicit tax on gasoline consumption and an implicit subsidy on ethanol consumption.*

fuels on food and fuel markets; we quantify these effects using a numerical simulation model. We use the numerical simulation model to examine the effects of these policies on the mix of biofuels and the magnitude of the domestic and global rebound effects and compare the relative magnitudes of the displacement effect, the rebound effects, and the ILUC effect for GHG emissions under various policies.

The numerical simulation is conducted using the dynamic, multi-market equilibrium, nonlinear mathematical programming model, Biofuel and Environmental Policy Analysis Model (BEPAM). The model simulates the transportation and agricultural sectors in the United States, including international trade with the ROW and endogenously determines the effects of biofuel and carbon policies on fuel mix, prices in markets for fuel, biofuel, food/feed crops, and on GHG emissions in the United States at annual time scales throughout the period of 2007-2030. As alternative fuels we consider first-generation biofuels produced domestically from corn and soybeans and imported sugarcane ethanol. We also consider various second-generation biofuels from cellulosic feedstocks, including crop and forest residues and dedicated energy crops. We distinguish between the domestic and global rebound effects of these policies on gasoline and diesel markets. We also compare the magnitudes of the rebound effect and the ILUC effect on GHG emissions using Environmental Protection Agency (EPA, 2010) estimates of the ILUC effect of biofuel production. We explore the sensitivity of the GHG mitigation effects of biofuel policies to fuel demand and supply elasticities and the magnitude of the ILUC effect estimated by other studies.

We show that the fuel displacement effect and the direct and indirect GHG effects differ across these policies due to differences in the ways in which these policies affect the mix of biofuels (with different carbon intensities) and food and fuel prices. Unlike a carbon price policy that raises the domestic consumer price of different fuels based on their carbon intensity and lowers consumption of fossil fuels, a biofuel quantity mandate (unlike a blend mandate or LCFS) displaces fossil fuels but creates no direct incentives to lower fossil fuel consumption. A LCFS creates a wedge between the consumer and producer price of fuel by implicitly taxing gasoline and implicitly subsidizing low-carbon fuels (Chen, Huang, Khanna, & Önal, 2011; Holland, Hughes, & Knittel, 2009). It operates more like a blend mandate in that it creates direct incentives to lower fossil fuel consumption and raise biofuel consumption. As a result, domestic gasoline consumption under a quantity mandate would be larger than that under a blend mandate if they achieve the same level of biofuel consumption. Furthermore, if the quantity mandate is accompanied by energy-equivalent pricing of biofuels, then it will lead to lower gasoline and biofuel prices as compared to those in the absence of the mandate. Thus, a quantity mandate will always lead to a positive domestic rebound effect on fossil fuel use, unlike a blend mandate or LCFS. However, the rebound effect of a quantity mandate in the ROW could be smaller because it would displace less gasoline than a blend mandate or LCFS that achieves the same level of biofuel consumption. On the other hand, if the LCFS induces a smaller volume of biofuels than a quantity mandate, then it would not only have a smaller domestic but also a smaller global rebound effect.

Moreover, while the mix of biofuels consumed under the RFS will be influenced by the nested volumetric quantities mandated, the LCFS allows greater flexibility to shift the mix of biofuel consumption toward low-carbon second-generation biofuels. The carbon tax will induce the mix and level of fuel consumption that reduces GHG emissions at the least cost after considering the reduction in fossil fuel consumption as an abatement option. Thus the direct displacement effect and the ILUC effect of biofuels will differ across these policies.

Conceptual Framework

We consider an open economy with homogeneous consumers that demand vehicle kilometers traveled (VKT), which are produced by blending gasoline and biofuels as perfect substitutes. We also assume that consumers have flex-fuel vehicles and a choice of fuel to consume; this implies that they will buy biofuels only if the consumer price of biofuels is the same as that of energy-equivalent gasoline. Gasoline can be produced domestically or imported from the ROW. For ease of illustration, the conceptual analysis considers one type of biofuel that can be blended with gasoline, but we relax this assumption in our numerical simulation.

The demand curve for VKT is D_m in Figure 1a. Supply curves for biofuels and domestic gasoline are assumed to be upward-sloping and represented by S_b and S_g in Figures 1b and 1c, respectively. We also consider gasoline demand and supply in the ROW; these are represented by RD_g and RS_g in Figure 1d. The marginal cost of VKT is determined by the marginal costs of gasoline and biofuels and denoted by S_m in Figure 1a. Consumers' demand for VKT yields derived demand curves for biofuels and gasoline, represented by D_b and D_g in

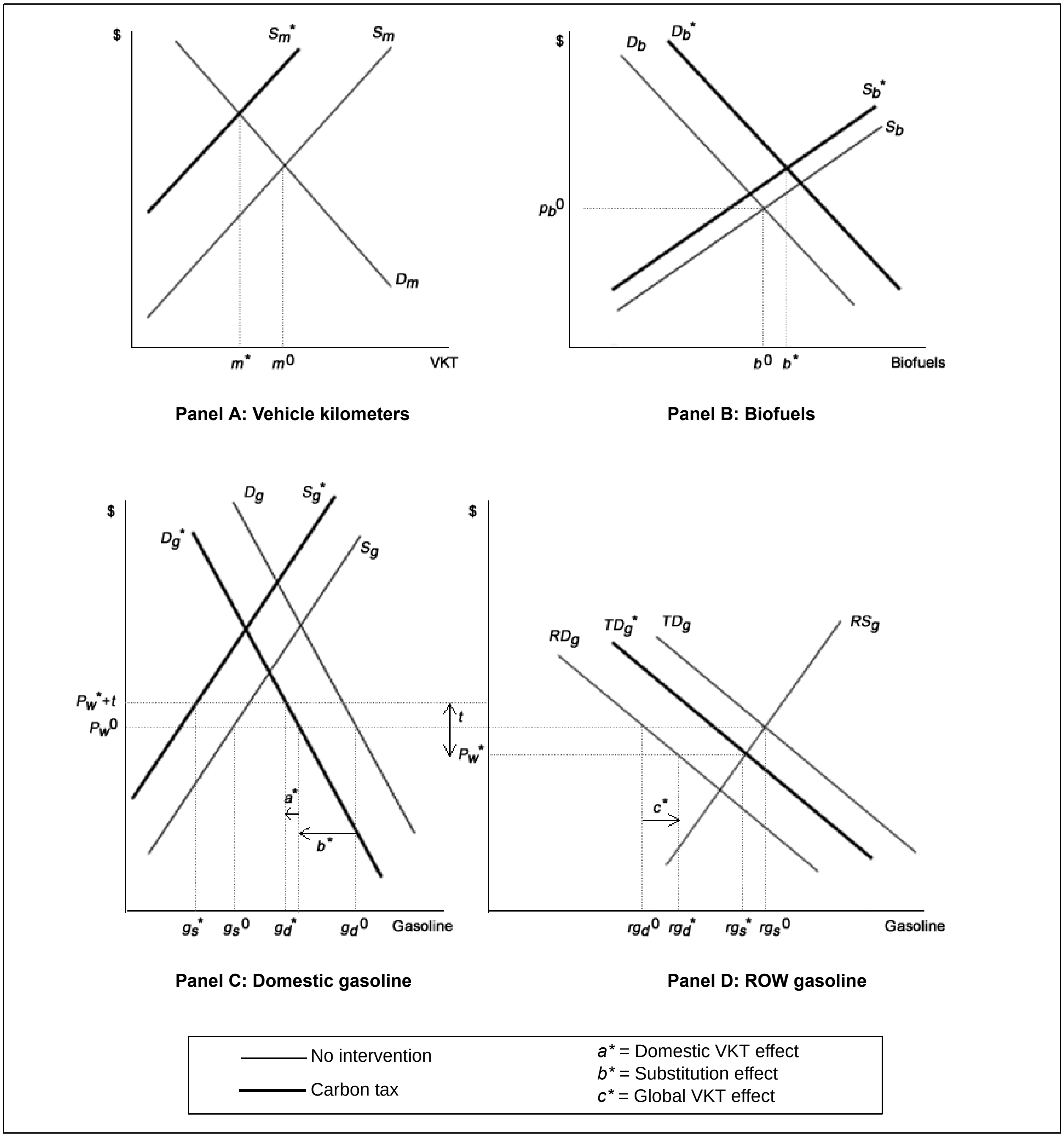

Figure 1. Effect of a carbon tax.

Figures 1b and 1c, respectively. Together with the ROW gasoline demand (RD_g), total demand for gasoline in the ROW market is represented by TD_g in Figure 1d.

In the absence of any government intervention in fuel markets, the market-equilibrium consumption of VKT (m^0), biofuels (b^0), domestic gasoline consumption and production (g_d^0 and g_s^0), and ROW gasoline consumption and production (rg_d^0 and rg_s^0) are shown in Figures 1a-1d. Note that in the market equilibrium, the excess supply of gasoline in the ROW ($rg_s^0 - rg_d^0$) is equal to US gasoline imports ($g_d^0 - g_s^0$), and biofuels are priced at the energy-equivalent price of gasoline p_w^0 that is determined in the ROW market.

We first analyze the effects of a carbon tax in this market and then compare its effects with those under a biofuel consumption mandate (such as the RFS) and a LCFS.

Carbon Tax

A carbon tax (t) will raise the marginal costs of biofuels and gasoline based on their carbon intensities and shift their marginal cost curves to the left to S_b* and S_g*, respectively, as shown in Figures 1b-1c. Since gasoline is more carbon intensive than biofuels, the shift in the marginal cost curve of gasoline is larger. Increased fuel costs raise the marginal cost of VKT and shift its marginal cost curve to the left to S_m*. The change in relative price of gasoline and biofuels also results in shifts in the derived demand curves for these fuels. The carbon tax decreases the price of biofuels relative to gasoline and thus increases the demand for biofuels and shifts its demand curve to the right (D_b*) while reducing the demand for gasoline and shifting its demand curve to the left (D_g*). Reduced US demand for gasoline lowers the demand for gasoline in the ROW market and shifts the total demand curve to the left (TD_g*), resulting in a reduction in the world price of gasoline to $p_w* < p_w^0$. Due to the carbon tax, US gasoline price will be $p_w* + t > p_w^0$. Therefore, the equilibrium levels of gasoline and VKT consumption decline to $g_d* < g_d^0$ and $m* < m^0$. Reduced world price of gasoline increases ROW gasoline consumption to $rg_d* > rg_d^0$.

With the marginal cost of biofuels and the derived demand for biofuels both increasing, biofuels consumption may increase or decrease depending on the elasticity of demand for VKT and the supply elasticity of gasoline (as shown in Chen et al., 2011). If the demand for VKT is fairly inelastic and the supply elasticity of gasoline is high, a small change in relative prices of fuels due to the carbon tax will lead to a relatively large substitution effect in favor of biofuels and a small VKT effect so that biofuel consumption will increase. On the other hand, if the demand for VKT is sensitive to the increase in fuel prices and gasoline supply curve is steep, a carbon tax will cause a large reduction in VKT; thus biofuels consumption is likely to decrease.

As illustrated in Figure 1c, the carbon tax reduces gasoline consumption and GHG emissions through two ways. First, it lowers the price of biofuels relative to gasoline and induces a substitution effect displacing gasoline with biofuels. Second, the carbon tax increases the cost of driving and thus leads to a negative VKT effect that decreases the total fuels consumption. Since the substitution and VKT effects move toward the same direction, the reduction in US gasoline consumption will be larger than the energy-equivalent increase in biofuels consumption, implying that there will be a negative domestic rebound effect on gasoline market. However, the global rebound effect could be positive or negative and expressed as $(c* - a*)/b*$, where $a*$ and $b*$ denote domestic VKT and substitution effects (see Figure 1c), respectively, while $c*$ is the increase in ROW gasoline consumption due to an increase in VKT induced by a lower fuel price (see Figure 1d). Its sign will depend on the magnitudes of $a*$ and $c*$. The global rebound effect is likely to be negative with an elastic ROW supply of gasoline and an elastic demand for VKT. With an elastic supply of gasoline, the biofuel-induced displacement of gasoline in the United States due to the carbon tax will not have a significant effect on the world price or consumption of gasoline, while an elastic demand for VKT in the United States will lead to a relatively large reduction in demand for gasoline in the United States.

Biofuel Mandate

Figure 2 illustrates the effect of a biofuel quantity mandate. The biofuel mandate of M liters, represented by the dark vertical line in Figure 2b, leads to a reduction in the demand for gasoline and shifts gasoline demand curves in the United States and ROW markets to the left to D_g^M and TD_g^M (in Figures 2c and 2d), respectively. Reduced gasoline demand in the United States reduces the world price of gasoline to $p_w^M < p_w^0$. Since consumers are assumed to have a choice of the fuel they consume and the price of biofuels is restricted to be the same as the energy-equivalent price of fossil fuels, the mandate will decrease the consumer price of fuel to $p_b^M < p_b^0$, as shown in Figure 2b. The gap between the producer price of biofuels ($p_b^{M'}$), which is needed to incentivize production of biofuels beyond the free-market level, and the consumer price of biofuels ($p_b^{M'} - p_b^M$) will be borne by fuel blenders. The mandate therefore reduces the consumer price of both gasoline and biofuels and thus lowers the cost of driving; the marginal cost of VKT shifts to the right to S_m^M, resulting in higher VKT consumption $m^M > m^0$ compared to the case with no government intervention. As a result, the biofuel mandate generates a positive VKT effect that offsets the substitution effect of biofuels on gasoline consumption (in Figure 2c), resulting in positive domestic and global rebound effects on gasoline markets. The magnitude of the domestic rebound effect can be expressed as a^M / b^M, where a^M and b^M represent the magnitudes of

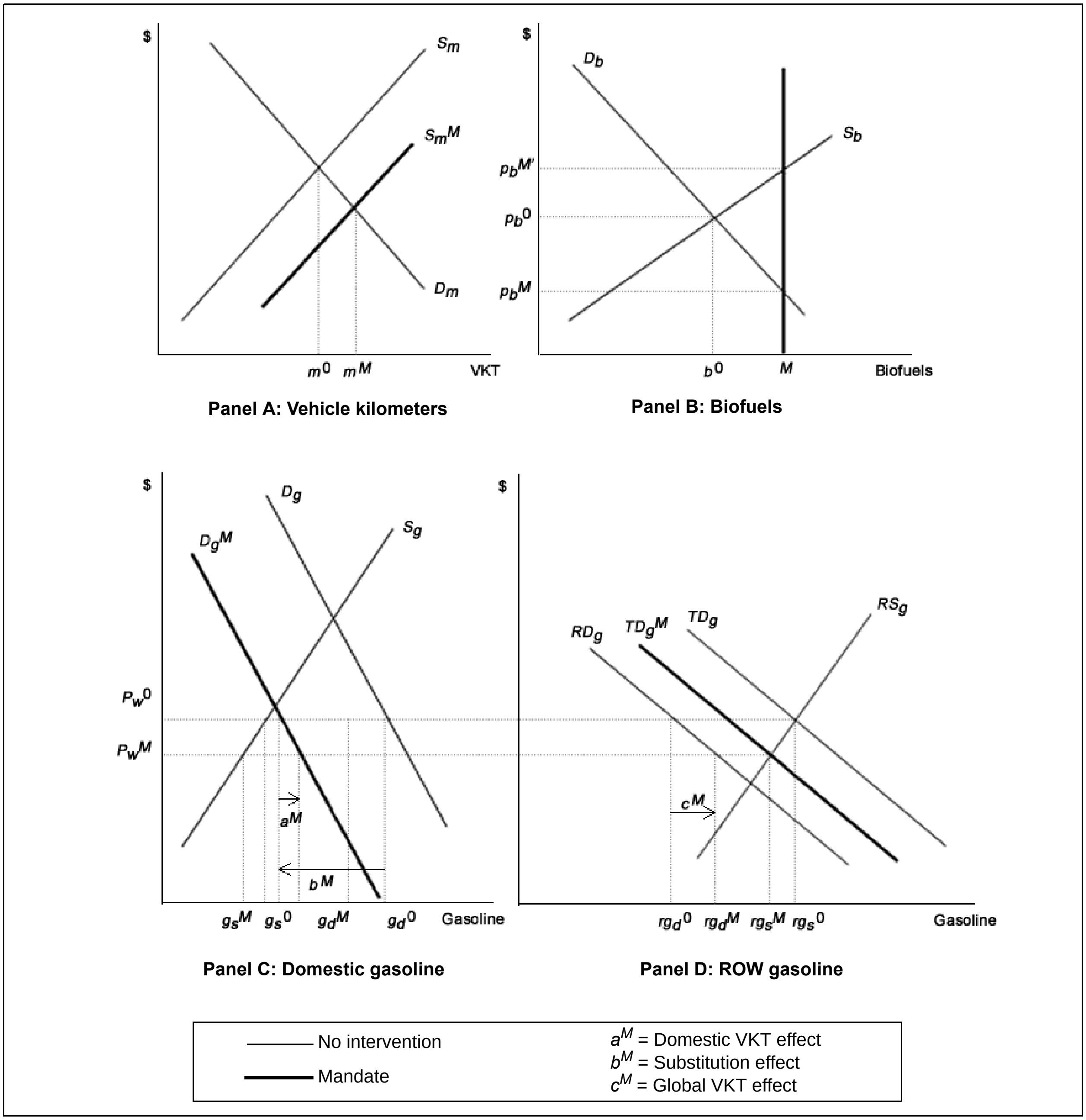

Figure 2. Effect of a biofuel consumption mandate.

domestic VKT and substitution effects as shown in Figures 2b and 2c, respectively. As compared to the domestic rebound effect, the global rebound effect is larger and represented by $(a^M + c^M)/b^M$, where c^M is the increase in gasoline consumption in the ROW due to increased global demand for VKT induced by the reduction in the world price of gasoline.

The net impact of the biofuel mandate on GHG emissions depends on the relative strengths of the substitution effect and the VKT effect and the relative carbon intensities of gasoline and biofuels. With a small VKT effect (if the demand curve for VKT is relatively inelastic) and a large substitution effect (if the supply curve of gasoline is relatively elastic), the mandate could result in a negative effect on domestic GHG emissions (see Chen et al., 2011).

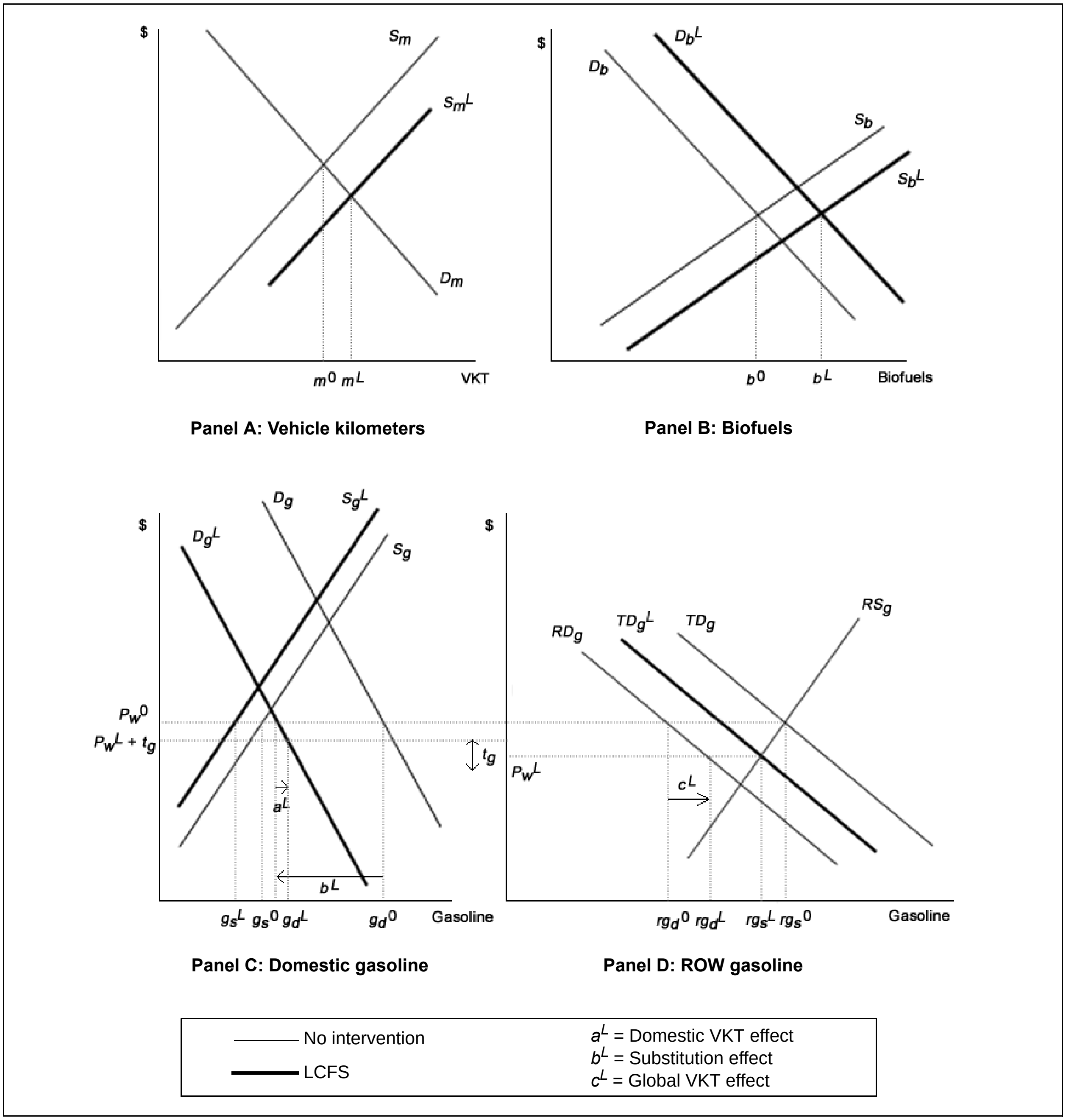

Figure 3. Effect of a LCFS that increases VKT.

Low Carbon Fuel Standard

A LCFS requires the carbon intensity of the blended fuel to be less than a given level σ where $\delta_e \leq \sigma \leq \delta_g$ and δ_e and δ_g are carbon intensities of biofuels and gasoline, respectively. That implies that a LCFS will provide an implicit subsidy to biofuels and impose an implicit tax on gasoline (Chen et al., 2011; Holland et al., 2009), and shift their supply curves to the right (S_b^L) and to the left (S_g^L) in Figures 3b and 3c, respectively. As the demand for gasoline in the domestic market falls, the total demand for gasoline in the ROW market declines to TD_g^L in Figure 3d, resulting in a reduced world price of gasoline $p_w^L < p_w^0$. Depending on the stringency of the LCFS that determines the implicit tax imposed on gaso-

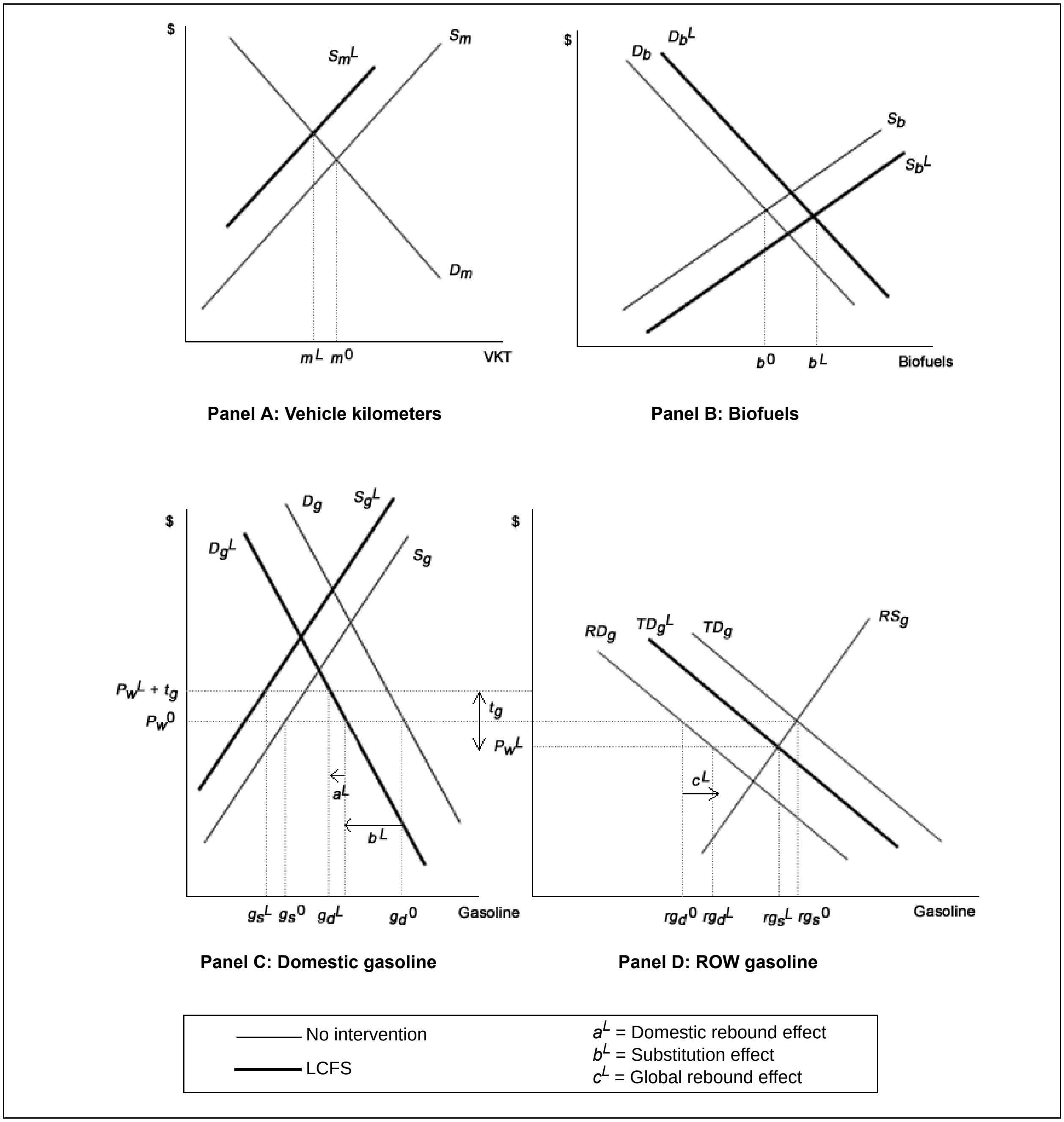

Figure 4. Effect of a LCFS that decreases VKT.

line (t_g), domestic gasoline price could be higher or lower than p_w^0. With a less stringent LCFS, domestic gasoline price will be $p_w^L + t_g < p_w^0$ as shown in Figure 3c. In this case, the LCFS will lower the marginal cost of VKT, shift its supply curve to the right to S_m^L in Figure 3a, and increase VKT consumption to $m^L > m^0$. Similar to a biofuel mandate, the positive VKT effect under the LCFS (see Figure 3c) will result in positive domestic and global rebound effects on gasoline markets with magnitudes of a^L/b^L and $(a^L + c^L)/b^L$, respectively (see Figures 3c and 3d). On the other hand, a stringent LCFS could raise domestic gasoline price to $p_w^L + t_g > p_w^0$ in Figure 4c and reduce VKT consumption, yielding a negative rebound effect on the domestic gasoline market. This is similar to the finding by Rajagopal et al. (2011) that biofuels can have a negative indirect fuel use effect.

With an elastic supply of ROW gasoline and an elastic demand for VKT, the reduction in domestic gasoline consumption may reduce or even negate the increase in ROW gasoline consumption, resulting in a negative global rebound effect. If the GHG intensity of biofuels is relatively low, the reduction in GHG emissions can be larger than that due to the displacement effect of biofuels.

Numerical Model

We now turn to the empirical analysis to quantify the direct and indirect effects of these policies using a multi-market, multi-period, price-endogenous mathematical programming model, Biofuel and Environmental Policy Analysis Model (BEPAM). BEPAM simulates consumption and production decisions in US agricultural and transportation fuel sectors, including international trade with the ROW. The model determines several endogenous variables simultaneously, including domestic production and consumption, export and import quantities of agricultural commodities, VKT, fuel and biofuel consumption, imports of gasoline, and sugarcane ethanol. Market equilibrium is achieved by equating demand and supply in US agricultural and fuel markets and trading partners.

Transportation Sector

The transportation sector considers demand curves of VKT for five types of vehicles, including conventional gasoline, flex fuel, gasoline-hybrid, electric, and diesel. VKT are produced by blending fossil fuels (gasoline and diesel) with biofuels as perfect substitutes. The VKT with electric vehicles are fixed exogenously. In producing VKT, we recognize the difference in energy content of alternative fuels, in fuel economy of each type of vehicle, and the technological limits on blending fossil fuels and biofuels for each type of vehicle. Details of the model can be found in Chen et al. (2011).

We include upward-sloping supply curves of gasoline produced in the United States and the ROW. The excess supply of gasoline from the ROW to the United States is determined by the difference between gasoline demand and supply in the ROW. In the case of diesel, we assume that it is produced domestically and therefore include an upward-sloping supply curve to represent its marginal cost of production and price responsiveness.

The biofuel sector includes several first- and second-generation biofuels. First-generation biofuels include domestically produced corn ethanol and imported sugarcane ethanol, biodiesel produced from soybean oil, distillers'-dried-grains-with-solubles (DDGS)-derived corn oil, and waste grease. As second-generation biofuels, we include cellulosic ethanol and biomass-to-liquids (BTL; blended with diesel) derived from cellulosic biomass such as crop or forest residues and energy crops. We use the experience curve approach to incorporate the reduction in processing costs of biofuels over time due to learning by doing (Witt, Junginger, Lensink, Londo, & Faaij, 2010).

Agricultural Sector

The agricultural sector in BEPAM considers production and consumption of major conventional crops, livestock products, bioenergy crops (miscanthus and switchgrass), and crop and forest residues in 295 US crop reporting districts (CRDs). It also considers 22 agricultural commodities being traded with the ROW. Demand functions for domestic consumption and for exports and imports of tradable commodities are specified separately for individual agricultural commodities. We shift demand curves upward over time at exogenously specified rates to capture the increase in demands due to the growth in population and income.

On the supply side, we consider spatial heterogeneity in crop and livestock production, where costs of production, yields, and land availability differ across CRDs. The model includes five types of land for each of the CRDs, including cropland, idle land, cropland pasture, permanent pasture land, and forestland pasture. Idle land and cropland pasture can be converted to the production of conventional crops in response to the changes in crop prices, while pasture land and forestland pasture are kept at 2007 levels. Crops can be produced using alternative rotation, tillage, and irrigation practices. Row crop yields are assumed to increase over time based on econometrically estimated trends and price responsiveness in the United States (see Chen et al., 2011). Yields of bioenergy crops are assumed to be the same on marginal lands (idle land and cropland pasture) and cropland, but vary regionally. The crop sector provides feed and byproducts of biofuel production as inputs for livestock production.

Data

The numerical simulation model is calibrated using 2007 consumption, production, and price data. A detailed description about the data used for the agricultural sector can be found in Chen et al. (2011). Here we describe the data sources for the transportation sector, which include the demand for VKT, the supply of alternative fuels, and specification of their GHG intensities.

Projected demand for VKT for each type of vehicle, fuel economy, and technological limits over 2007-2030 are taken from Annual Energy Outlook (2010). We obtain fuel and biofuel consumed by on-road vehicles in 2007 from Davis, Diegel, and Boundy (2011) and their prices from Energy Information Administration (EIA, 2010). We use a demand elasticity of -0.2 to calibrate demand curves of VKT (Parry & Small, 2005). Short-run supply elasticity of US gasoline and diesel are assumed to be the same and equal 0.049 (Greene & Tishchishyna, 2000). We assume a value of -0.26 for the elasticity of ROW gasoline demand, and an elasticity of 0.2 for short- run gasoline supply in the ROW (Leiby, 2007). We shift the demand curve for gasoline for the ROW to the right at the exogenously fixed rate of 1%, based on the historically observed increase in ROW gasoline consumption (EPA, 2010).

While feedstock costs of biofuels are endogenously determined in the agricultural sector, we collect conversion rates of processing feedstocks to biofuels from several sources, including GREET 1.8c for corn ethanol, Forest and Agricultural Sector Optimization Model (FASOM) for biodiesels derived from vegetable oils or waste grease (Beach & McCarl, 2010), Business Wire for biodiesel from DDGS-derived corn oil,[4] and EPA for BTL and cellulosic ethanol (EPA, 2010). The parameters of the experience curves for each type of biofuel are obtained from various sources; biofuel processing costs are obtained from EPA (2010); Swanson, Platon, Satrio, and Brown (2010); and Crago, Khanna, Barton, Amaral, and Guiliani (2010), while the learning rates are obtained from Witt et al. (2010). We use US ethanol retail prices and imports from Brazil and CBI countries in 2007, as well as an assumed elasticity of the excess supply of ethanol imports of 2.7 to calibrate the excess supply curves of ethanol imports (Lee & Sumner, 2009). The cost of production of imported sugarcane ethanol is assumed to decline over time due to the growth of ethanol industry in Brazil (Van Den Wall Bake, Junginger, Faaij, Poot, & Walter, 2009).

We specify the life-cycle GHG intensity of alternative transportation fuels. Life-cycle GHG emissions intensity of conventional gasoline is 93.05g CO_2e/MJ and of petro diesel fuel is 91.95g CO_2e/MJ in 2005. These carbon intensities are assumed to increase over time due to imports of high-carbon-intensive fuels, like oil tarsands. Estimates for life-cycle GHG emissions of biofuels include emissions from feedstock production, biofuel conversion, distribution, and consumption. The agricultural-phase GHG emissions include emissions from agricultural input uses such as fertilizer, chemicals, fuels and machinery, and soil carbon sequestration. These input-use data are obtained from region-specific crop budgets while the life-cycle GHG emission factors for these inputs are derived from GREET 1.8c (see Chen et al., 2011). We also obtain GHG emissions of biofuel conversion, distribution, and use from GREET 1.8c. We assume a carbon intensity of 25.12g CO_2e/MJ for sugarcane ethanol obtained from Crago et al. (2010). The GHG emissions intensity effects due to ILUC are the average estimates obtained by EPA (2010), with 30.33g CO_2e/MJ for corn ethanol, 40.76g CO_2e/MJ for soybean oil diesel, 3.79g CO_2e/MJ for Brazilian sugarcane ethanol, and 14.22g CO_2e/MJ for all biomass based biofuels. We also consider the effects of assuming the ILUC-related intensities of various biofuels are 100% higher than these average values.

Results

We simulate the model under three policy scenarios: a carbon tax, the RFS, and a national LCFS. Since climate change legislation is yet to be enacted in the United States, we assume a $60 per metric ton of CO_2e over the period of 2007-2030 for the analysis considered here. According to the Annual Energy Outlook (2010), the requirement for cellulosic biofuels specified by the EISA of 2007 is unlikely to be achieved by 2022. Instead, we use the AEO (2010) projections for annual volumes of first- and second- generation biofuels production over the 2007-2030 period to set the biofuel consumption mandate, and we assume the production of cellulosic biofuels will first start in 2015. The AEO projections set an upper limit of 57B liters on the amount of corn ethanol in meeting the mandate in 2015 and beyond, and total biofuel production should be at least 143 ethanol energy-equivalent liters in 2030. A national LCFS restricts GHG emissions per unit of energy consumed in the transportation fuel sector to be below a specified intensity level for a given year. We consider a LCFS that lowers the average fuel carbon intensity by 10% by 2030 relative to the combined carbon intensity of conventional gasoline and petro-diesel in 2005. Annual rates of reduction in GHG intensity are set linearly to meet these targets between 2015 and 2030.

4. *http://www.businesswire.com/news/home/20061109005429/en*

Table 1. Effects of biofuel and climate policies.

Scenarios	BAU 2007	BAU	Carbon tax	Mandate	LCFS 10%	LCFS 20%
Consumer prices of fuels in 2030 ($ per liter)						
US gasoline price	0.73	0.95	1.11	0.85	0.91	1.04
US diesel price	0.77	0.98	1.14	0.97	0.95	0.85
World gasoline price	0.73	0.95	0.93	0.85	0.86	0.83
VKT and fuel consumption in 2030 (billion kilometers or liters)						
VKT	5173.7	7341.8	7118.1	7487.3	7409.9	7304.1
First-generation ethanol (a)	18.2	18.3	20.2	45.1	20.1	20.3
Cellulosic ethanol (b)				94.8	100.8	123.4
First-generation biodiesel[1] (c)		0.6	1.0	1.9	0.9	0.9
BTL[1] (d)					13.0	54.8
US gasoline (e)	500.8	504.4	487.5	434.6	440.9	416.0
ROW gasoline (f)	653.6	737.0	745.3	767.1	764.4	774.9
US diesel (g)	154.9	180.7	174.5	179.9	168.7	130.5
Rebound effects in 2030 (%)[2]						
US gasoline market: [0.67*(Δa+Δb)+Δe]/[0.67*(Δa+Δb)]				13.8	7.2	-5.7
Global gasoline market: [0.67*(Δa+Δb)+Δe+Δf]/[0.67*(Δa+Δb)]				51.1	47.3	39.7
US diesel market: (Δc+Δd+Δg)/(Δc+Δd)				37.0	10.0	9.0
Cumulative GHG emissions (2007-2030; billion metric tons)[3]						
US GHG emissions		52.3	49.8 (-4.7)	50.2 (-3.9)	49.8 (-4.8)	48.0 (-8.2)
Direct savings due to displacement			0.6	2.5	2.7	4.5
Offset by domestic rebound effect			-1.9	0.5	0.2	0.2
US net savings			2.5	2.0	2.5	4.3
Offset by rebound effect in ROW			0.6	1.1	0.7	1.2
Offset by international ILUC			0.01	0.6	0.3	0.5
Net GHG savings with ILUC			1.9 (-3.6)	0.3 (-0.6)	1.5 (-2.8)	2.5 (-4.8)
Net GHG savings with high ILUC			1.9 (-3.6)	-0.3 (0.6)	1.1 (-2.2)	2.0 (-3.8)

1. Diesel energy equivalent liters.

2. Symbol Δ denotes fuel consumption under policy scenario minus fuel consumption under the BAU. Δa and Δb are measured in ethanol energy-equivalent liters while Δc and Δd are diesel energy-equivalent liters.

3. Numbers in parentheses represent the percentage changes in GHG emissions relative to the US GHG emissions under the BAU scenario.

We compare the effects of biofuel and climate policies on fuel consumption, domestic and global rebound effects on fuel markets, and GHG emissions with those under a business-as-usual (BAU) scenario defined as no government intervention in biofuel markets, and results are shown in Table 1.

Model Validation

We first validate the simulation model for 2007 assuming existing fuel taxes, corn ethanol mandate, corn ethanol tax credit, and import tariffs, and compare the model results on land allocation, commodity prices, and fuel prices and consumption with the corresponding observed values in 2007. We find the differences between model results and the observed land use allocations and commodity prices for major crops are typically less than 10%. Fuel prices and consumption are also simulated well with the difference from observations being less than 5% (see Chen et al., 2012).

Business-as-usual Scenario

The shift in demand for VKT increases total VKT consumption (including gasoline- and diesel-based VKT) in 2030 by 42% compared to the 2007 level. Due to the projected increase in vehicle fuel economy by AEO (2010), we find gasoline and diesel consumption will increase by 0.7% and 17%, respectively, while biofuels consumption rises by 6%. The production of ethanol is simply to meet the requirements as a fuel additive. Growth in population and income in the ROW increases ROW gasoline consumption by 13% over the 2007-2030 period. The increase in demand for gasoline raises the price of gasoline by 30% and the price of diesel by 26% over this period. Cumulative GHG emissions in the United States over the 2007-2030 period are 52.3B tons.

We now examine the effect of alternative policies on the domestic emissions by the United States and the emissions in the ROW due to the ILUC effect and the rebound effect on gasoline consumption in the ROW.

Effects of Low Carbon Policies

Carbon Tax. A carbon tax of $60 per metric ton of CO_2e will lead to an increase in US gasoline and diesel prices by 17% relative to the BAU scenario and reduce their consumption in the United States in 2030 by 3%. It leads to 20.2B liters of biofuel consumption, which is 13% larger than the level consumed under the BAU scenario. Biofuel consumption is primarily in the form of domestically produced corn ethanol and imported sugarcane ethanol since the tax is not high enough to induce the production of cellulosic biofuels by 2030. The carbon tax also reduces VKT by 3% due to increased fuel costs compared to the BAU scenario. By lowering the demand for gasoline imports, the carbon tax reduces the world price of gasoline by 3%. This increases ROW gasoline consumption by 1%. However, the domestic and global rebound effects on gasoline markets and domestic rebound effect on the diesel market are negative, implying that the reduction in fossil fuel consumption is greater than the energy-equivalent increase in biofuel consumption. The displacement in GHG emissions, cumulated over the 2007-2030 period due to the carbon-tax-induced biofuel production is 0.6B tons. The rise in fuel prices due to the carbon tax reduces VKT and leads to a negative domestic rebound effect, which further reduces emissions by 1.9B tons. Together these factors lower cumulative US GHG emissions by 2.5B tons (4.7%) compared to the BAU scenario over the 2007-2030 period. These savings are offset by about 0.6B tons due to the positive fuel rebound effect in the ROW, leading to a net decline in US GHG emissions savings by 3.6% as compared to the BAU scenario. Due to the small amount of biofuel produced under the carbon tax, we find the inclusion of the ILUC-related GHG intensity of biofuels does not significantly erode the GHG savings as shown in Table 1.

RFS. The requirement for 143B liters of biofuel production in 2030 under the RFS is met by 48.3B liters of first-generation biofuels and 94.8B liters of second-generation biofuels (ethanol energy-equivalent liters). The RFS-induced biofuel production reduces the demand for gasoline and diesel in the United States by 14% and 0.5%, respectively, compared to the BAU levels. Reduced US demand for gasoline leads to a reduction in the world price of gasoline by 10% and stimulates gasoline consumption in the ROW by 4% relative to the BAU scenario. Unlike the carbon tax that reduces VKT consumption by increasing the costs of driving, the RFS will increase VKT by 2% compared to the BAU scenario. Therefore, the rebound effect is positive and the reduction in domestic gasoline consumption is 14% lower than the energy-equivalent increase in ethanol consumption, while the reduction in diesel consumption is 37% lower than the energy-equivalent increase in biodiesel consumption in 2030. As expected based on Figure 2d, the global rebound effect on the gasoline market is larger (51%) than the domestic rebound effect. The large amount of biofuels consumed under the RFS displaces GHG emissions by 2.5B tons, which is significantly larger than that achieved by the carbon-tax policy. However, the positive domestic rebound effect offsets this GHG saving by 0.5B tons, leading to a reduction in cumulative US GHG emissions by 2.0B tons only (or 3.9%) compared to the BAU scenario. The positive fuel rebound effect in the ROW further offsets these savings by another 1.1B tons while the ILUC effect reduces these savings by 0.6B tons. As a result, the net reduction in GHG emissions will be only 0.6% compared to the US GHG emissions in the BAU scenario over the 2007-2030 period. With high estimates of ILUC-related GHG emissions, the change in GHG emissions as a percentage of US GHG emissions will be an increase of 0.6% relative to the BAU scenario.

The findings obtained here differ from those obtained by Bento et al. (2011), Drabik and de Gorter (2011), and Rajagopal et al. (2011) for the effects of a biofuel mandate on GHG emissions for several reasons. First, the mix of biofuels produced here results in a much higher direct GHG savings of 65% on average for each megajoule of fossil fuel displaced by biofuels as compared to the studies above. The corresponding emissions savings with corn ethanol are assumed to be about 43% in Bento et al. (2011) and 21-52% in Drabik and de Gorter (2011). This is due to the mix of biofuels considered here, which includes cellulosic biofuels with a much lower GHG intensity compared to fossil fuels. Second, unlike the above studies that consider a blend mandate and assume the blended fuel is priced as the weighted average of the prices of gasoline and biofuels, we find that the domestic rebound effect is positive rather than negative because we consider a quantity mandate with energy-equivalent pricing. Third, the magnitude of the rebound effect will also depend on the elasticity of demand for VKT or blended fuel and the elasticity of supply for fuel. As the elasticity of fuel supply decreases, the biofuel-induced reduction in demand for gasoline will lead to a larger reduction in world gasoline price. In contrast to our assumption of an elasticity of domestic demand for VKT of -0.2, and the assumption of inelastic global demand for fuel of -0.26, Bento et al. (2011) assume the elasticity of demand for VKT of -0.53; this could explain their large rebound effect ranging from (-)75% to (-)170% in the 2012-2015 period. On the other hand, the elasticity of oil supply in the ROW is assumed to be very low (0.04) in Bento et al. (2011) as compared to 0.2 here and in Drabik and de Gorter (2011), and values ranging from 0.3 to 0.4 in Rajagopal et al. (2011). Despite the positive domestic and global rebound effects and the ILUC effect estimated here, we find that the mandate has a small but negative impact on global GHG emissions (with the average ILUC effect) due to the large displacement effect with low-carbon cellulosic biofuels. We discuss the sensitivity of our estimate to various parametric assumptions in the next section.

LCFS. As compared to the RFS, the LCFS promotes greater consumption of second-generation biofuels due to their low carbon intensity. Of the total biofuel consumed in 2030 (145 ethanol energy-equivalent B liters), we find second-generation biofuels (cellulosic ethanol and BTL) will account for 85% (123B liters) while the rest comes from first-generation biofuels (22B liters). The large volume of biofuel consumption leads to a significant reduction in US gasoline and diesel consumption in 2030 by 13% and 7%, respectively, relative to the BAU scenario. Reduced demand for gasoline in the United States benefits consumers in the ROW by lowering the world price of gasoline by 9%; this leads to a 4% increase in ROW gasoline consumption. VKT consumption under the LCFS will be 0.9% higher than that under the BAU scenario, but 1% smaller relative to the RFS. Therefore, the rebound effects on domestic gasoline and diesel markets are also smaller and equal to 7% and 10%, respectively. The global rebound effect on the gasoline market is 47% instead of 51% under the RFS. The displacement effect reduces GHG emissions by 2.7B tons. The small positive domestic rebound effect offsets GHG saving by 0.2B tons, leading to a net reduction in cumulative US GHG emissions by 2.5B tons (or 4.8%) compared to the BAU scenario. The global rebound effect offsets these GHG savings by about 0.7B tons and is smaller than under the RFS. Moreover, due to the large amount of cellulosic biofuels produced under the LCFS, we find the ILUC-related emissions only offset the GHG savings by 0.3B tons. As a result, we find the net reduction in GHG emissions as a percentage of US GHG emissions under the LCFS will be 2.8% compared to the BAU scenario. Even with high estimates of ILUC-related GHG emissions, the LCFS still results in a net reduction in GHG emissions by 2.2% relative to the BAU scenario.

We also examined the effects of a more stringent LCFS that would reduce average fuel carbon intensity by 20% in 2030 relative to the level in 2005. In this case, we find that the consumer price of gasoline in the United States would increase and VKT would fall resulting in a negative domestic rebound effect as shown in Figure 4. The global rebound effect on gasoline is smaller at 40%. The reduction in domestic GHG emissions would now be 8.2%, while the net reduction in GHG emissions (including the rebound and ILUC effect) would be 4.8% compared to the US GHG emissions under the BAU scenario and larger than under any other scenario considered here.

Sensitivity Analysis

The rebound effects and GHG impacts of these climate and biofuels policies depend on a number of behavioral parameters. We examine the sensitivity of our model results to assumptions about the demand elasticity of VKT and the supply elasticity of gasoline in the ROW. We consider cases with a higher elasticity of demand for VKT of -0.4 instead of -0.2 in Scenario 1 and lower supply elasticity of gasoline in the ROW market of 0.04 instead of 0.2 in Scenario 2. We also consider a case with higher supply elasticity of gasoline in the ROW market of 0.4 in Scenario 3. The higher elasticity of demand will lead to a larger VKT effect in response to changes in consumer prices of fuels and result in a larger

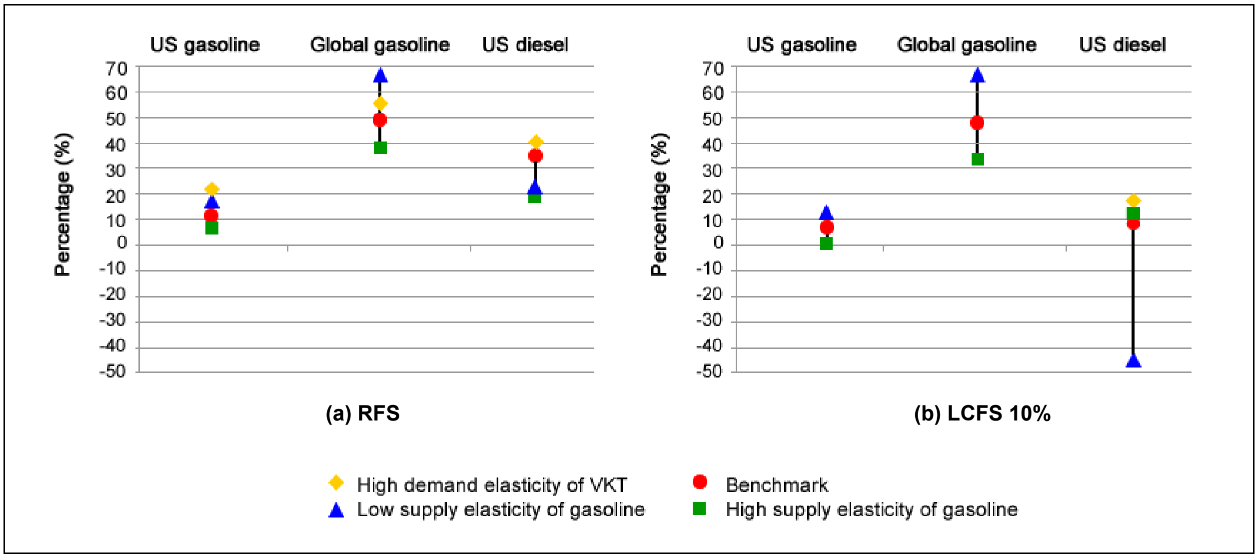

Figure 5. Effects of changes in parametric assumptions on the rebound effect in 2030.
Rebound effect as defined in Table 1 is measured on the vertical axis.

rebound effect of the RFS and LCFS. A lower (higher) elasticity of gasoline supply will also increase (decrease) the rebound effect of these policies by leading to a larger (smaller) reduction in fossil fuel price as demand falls. Changes in the elasticity of supply of gasoline will also have an effect on the diesel market because it will affect the mix of biofuels and the relative competitiveness of cellulosic ethanol and BTL. We present the ranges in domestic and global rebound effects on gasoline and diesel markets in 2030 under the RFS and LCFS in Figure 5. The carbon tax generates no rebound effect domestically and its global rebound effect is negligible (less than 1%). We also show the sensitivity of the percentage reductions in cumulative GHG emissions to these assumptions under these policies relative to their corresponding BAU levels in Figure 6.

As shown in Figure 5a, the global rebound effect on gasoline market under the RFS ranges from 39% to 68% and is larger than the domestic rebound effect (9% to 23%). The domestic rebound effect on the diesel market ranges from 20-40%. As compared to the RFS, domestic and global rebound effects under the 10% LCFS are smaller and range from 0.4% to 13% and 33% to 66%, respectively (see Figure 5b). As gasoline supply becomes more inelastic, the LCFS will lead to a larger reduction in gasoline price and the increase in the price of gasoline-based VKT will be smaller than that of diesel-based VKT. It will therefore be cost-effective to meet the LCFS through a larger reduction in diesel consumption that exceeds the increase in BTL consumption resulting in a negative rebound effect on diesel consumption.

In general, we find that changes in behavioral parameters in the fuel sector have a larger effect on the size of the rebound effect than on GHG emissions relative to the benchmark scenario. Across the scenarios considered here we find the carbon tax leads to the largest reduction in domestic GHG emissions, ranging from 4.6-7.3%. Even after considering the global effects of the carbon tax on food and fuel prices, the net reduction in GHG emissions ranges between 3.0-5.3% as a percentage of US GHG emissions in the BAU. The RFS and the LCFS lead to similar reductions in GHG emissions due to the displacement effect (about 5%; see Figure 6). The inclusion of global rebound and high ILUC effects under the RFS could offset these entire GHG savings, leading to a net increase in GHG emissions by 0.1-1.6% relative to the US GHG emissions under the BAU scenario. On the other hand, even after accounting for the global rebound effect and high ILUC-related emissions, the net reduction in GHG emissions under the LCFS lies between 1.3% and 2.7% compared to the BAU scenario. Thus, the carbon tax and the LCFS lead to a larger reduction in GHG emissions even after considering market-mediated effects as compared to the RFS under all parametric assumptions considered here.

Conclusions

This article shows that low-carbon fuel policies differ in their displacement and market-mediated effects on fuel

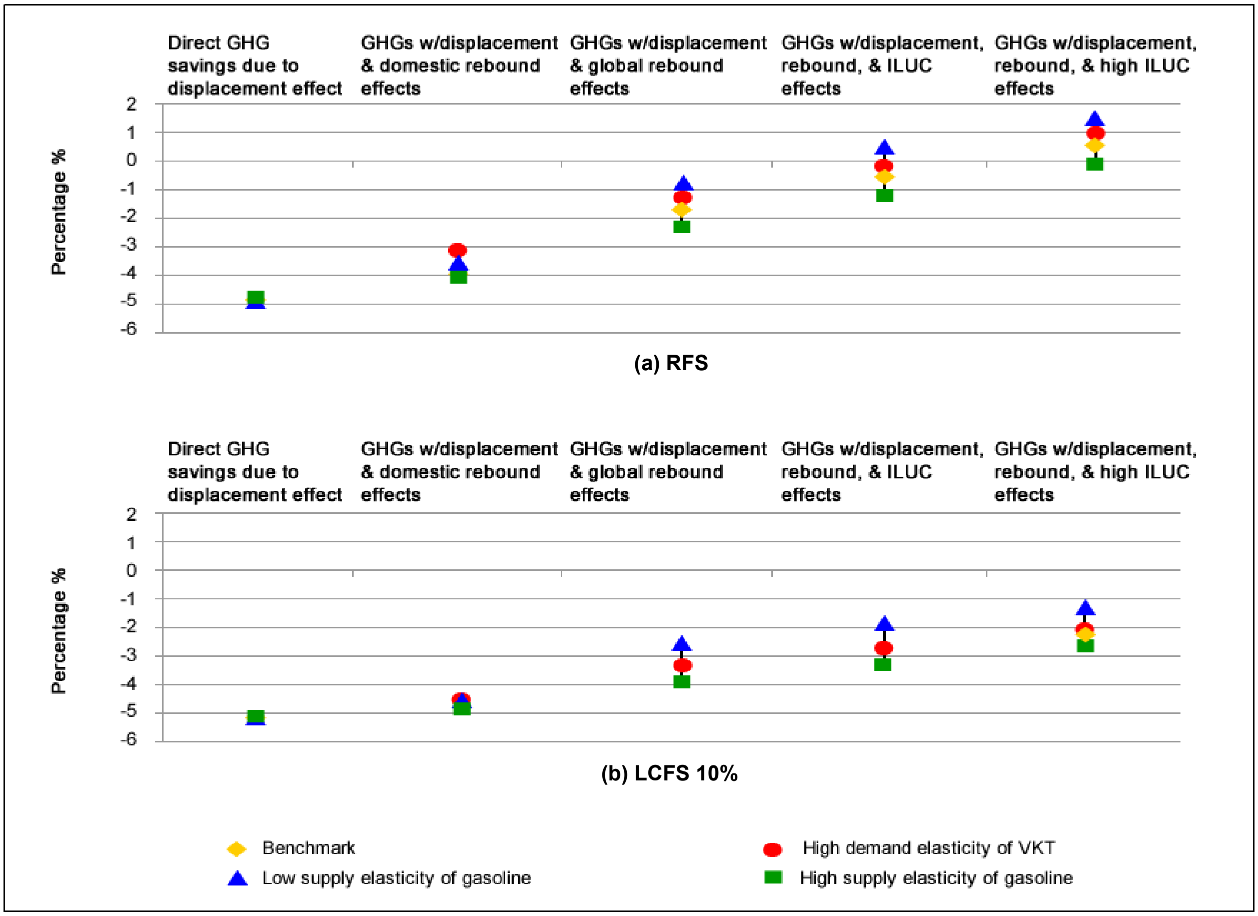

Figure 6. Effects of changes in parametric assumptions on cumulative GHG emissions (2007-2030).
Percentage change is measured relative to US GHG emissions in corresponding BAU scenarios).

consumption and on GHG emissions. A carbon tax policy would achieve emissions reduction primarily by reducing fuel consumption rather than inducing a switch to low-carbon fuels. A LCFS would create greater incentives to consume second-generation biofuels than the RFS. Despite a similar level of total biofuel consumption under the RFS and LCFS, the reduction in domestic GHG emissions under the LCFS is larger relative to the RFS due to this higher share of second-generation biofuels in the mix of biofuels.

These policies also differ in their effect on fuel prices. Policies that lead to relatively high consumer price of fuel compared to the BAU, like the LCFS (or the carbon tax), have a smaller (negative) domestic rebound effect. With a carbon tax, domestic fossil fuel use and GHG emissions will always decrease by more than the energy-equivalent increase in biofuels because the tax raises the price of both fossil fuel and biofuels. A relatively stringent LCFS could also have a negative domestic rebound effect, particularly if the elasticity of domestic fossil fuel supply is high. In contrast, a biofuel quantity mandate always results in a positive domestic rebound effect because it lowers the price of fossil fuels and thus the energy-equivalent price of biofuels. Our assumption of energy-equivalent pricing of biofuels is based on the expectation that the adoption of flex-fuel cars—needed to consume the large volumes of biofuel considered here by 2030—will provide consumers a choice of the blend they consume. If that is not the case and the government imposes a minimum blending requirement of 10% or so, then it would raise the price of the blended fuel to be higher than the energy-equivalent price of gasoline and reduce the size of the domestic rebound effect; this would contribute to greater GHG savings with these policies than those obtained here. For this reason, our estimate of the domestic GHG savings due to these policies is likely to be a lower bound.

Unilateral low-carbon policies are likely to have a positive rebound effect in the fuel market in the rest of the world and to lead to leakages due to land-use change. While these market-mediated effects have the potential to offset the GHG savings due to the displacement of fossil fuels by biofuels, our numerical simulations show that under a reasonable set of parametric assumptions and with the availability of low-carbon advanced biofuels, these policies can result in a net reduction in GHG emissions. The extent of these reductions differs across policies and depends on assumptions about fuel supply and demand elasticities as well as about the magnitude of the ILUC effect. The likely range of the change in GHG emissions with the average ILUC effect is (-)1.2% to 0.4% under the RFS, (-)1.9% to (-)3.3% under the LCFS, and (-)3% to (-)5.3% under a $60 per-metric-ton carbon tax policy relative to US GHG emissions under the BAU scenario over the 2007-2030 period.

The estimate of ILUC-related GHG emissions intensity used for biofuels was assumed to remain the same across the policies analyzed here. These policies differ in their effect on food prices due to differences in the mix of biofuels they induce. Thus, the ILUC-related GHG intensity should vary across policies. The volume of first-generation biofuels under the LCFS is less than half of that under the RFS. The effects of the LCFS on food prices should therefore be substantially smaller than that of the RFS and thus the ILUC-related GHG intensity of corn ethanol should be correspondingly smaller. A smaller ILUC-related GHG intensity of biofuels under the LCFS would increase the gap in the GHG savings achieved by the RFS and the LCFS. Among the market-mediated effects, we find that the rebound effect reduces GHG savings by twice as much as the ILUC effect (even when the high ILUC effect is considered).

Low-carbon policies in the United States have sought to address the ILUC effect by including the ILUC-related GHG intensity of a biofuel in the GHG intensity of that biofuel used to determine compliance with the RFS and LCFS. Given the magnitude of the rebound effect, this approach is only partially addressing the leakage problem. However, the sensitivity of the rebound effect to parametric assumptions, like in the case of the estimates of the ILUC effect, will make the choice of a leakage factor for implementing low-carbon regulations, such as the RFS and LCFS, subjective. Moreover, these are not the only market-mediated effects of biofuels; controlling some and not others will be an arbitrary decision (Khanna et al., 2011). Our results imply the need for global policies to effectively address a global problem like GHG mitigation rather than a piecemeal approach that addresses one leakage at a time.

References

Beach, R.H., & McCarl, B.A. (2010). *U.S. agricultural and forestry impacts of the energy independence and security act: FASOM results and model description*. Research Triangle Park, NC: RTI International.

Bento, A.M., Klotz, R., & Landry, J.R. (2011, July 24). *Are there carbon savings from US biofuel policies? Accounting for leakage in land and fuel markets*. Paper presented at the 2011 Agricultural & Applied Economics Association Annual Meeting, Pittsburgh, PA.

California Air Resources Board (CARB). (2009, March 5). *Proposed regulation to implement the low carbon fuel standard volume I* (Staff Report: Initial Statements of Reason). Sacramento, CA: Author. Available on the World Wide Web: http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol1.pdf.

Carlton, D.W., & Perloff, J.M. (2000). *Modern industrial organization* (3rd ed.). Reading, MA: Addison Wesley Longman, Inc.

Chen, X., Huang, H., Khanna, M., & Önal, H. (2011). *Meeting the mandate for biofuels: Implications for land use and food and fuel prices* (NBER Working Paper No. 16697). Cambridge, MA: National Bureau of Economic Research (NBER).

Chen, X., Huang, H., Khanna, M., & Önal, H. (2012). *Alternative transportation fuel standards: Welfare effects and climate benefits* (Energy Biosciences Institute Working Paper). Urbana: University of Illinois at Urbana-Champaign. Available on the World Wide Web: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1907766.

Crago, C., Khanna, M., Barton, J.B., Amaral, W., & Guiliani, E. (2010). Cost competitiveness of sugarcane ethanol in Brazil relative to corn ethanol in the US. *Energy Policy*, *38*(11), 7404-7415.

Davis, S.C., Diegel, S.W., & Boundy R.G. (2011).*Transportation energy data book: Edition 29*. Oak Ridge, TN: Oak Ridge National Laboratory.

Drabik, D., & de Gorter, H. (2011). Biofuel policies and carbon leakage. *AgBioForum*, *14*(3), 104-110. Available on the World Wide Web: http://www.agbioforum.org.

Du, X., & Hayes, D.J. (2009). The impact of ethanol production on US and regional gasoline markets. *Energy Policy*, *37*(8), 3227-3234.

Energy Information Administration (EIA). (2010). *Annual energy outlook 2010: With projections to 2035*. Washington, DC: Office of Integrated Analysis and Forecasting, US Department of Energy.

Environmental Protection Agency (EPA). (2010). *Renewable fuel standard program (RFS2) regulatory impact analysis*. Washington, DC: Author. Available on the World Wide Web: http://www.epa.gov/otaq/fuels/renewablefuels/index.htm.

Greene, D.L., & Tishchishyna, N.I. (2000). *Costs of oil dependence: A 2000 update*. Oak Ridge, TN: Oak Ridge National Laboratory.

Hochman, G., Rajagopal, D., & Zilberman, D. (2010). The effect of biofuels on crude oil markets. *AgBioForum*, *13*(2), 112-118. Available on the World Wide Web: http://www.agbioforum.org.

Holland, S.P., Hughes, J.E., & Knittel, C.R. (2009). Greenhouse gas reductions under low carbon fuel standards? *American Economic Journal: Economic Policy*, *1*(1), 106-146.

Khanna, M., & Crago, C.L. (2012). Measuring indirect land use change: Implications for policy. *Annual Review of Resource Economics*, *4*.

Khanna, M., Crago, C.L., & Black, M. (2011). Can biofuels be a solution to climate change? The implications of land use change-related emissions for policy. *Interface Focus*, *1*(2), 233-247.

Lee, H., & Sumner, D.A. (2009). *International trade patterns and policy for ethanol in the United States*. In M. Khanna., J. Scheffran, & D. Zilberman (Eds.), *Handbook of bioenergy economics and policy* (pp. 327-346). New York: Springer Publishers.

Leiby, P. (2007). *Estimating the energy security benefits of reduced U.S. oil imports: Final report*. Oak Ridge, TN: Oak Ridge National Laboratory.

Parry, I.W.H., & Small, K.A. (2005). Does Britain or the United States have the right gasoline tax? *American Economic Review*, *95*(4), 1276-1289.

Rajagopal, D., Hochman, G., & Zilberman, D. (2011). Indirect fuel use change (IFUC) and the lifecycle environmental impact of biofuel policies. *Energy Policy,* 39(1), 228-233.

Sinn, H.-W. (2008). Public policies against global warming: A supply side approach. *International Tax and Public Finance*, *15*(4), 360-394.

Swanson, R.M., Platon, A., Satrio, J.A., & Brown, R.C. (2010). Techno-economic analysis of biomass-to-liquids production based on gasification. *Fuel*, *89*(1), S11-S19.

Thompson, W., Whistance, J., & Meyer, S. (2011). Effects of US biofuel policies on US and world petroleum product markets with consequences for greenhouse gas emissions. *Energy Policy*, *39*(9), 5509-5518.

Van Den Wall Bake, J.D., Junginger, M., Faaij, A., Poot, T., & Walter, A. (2009). Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass and Bioenergy*, *33*, 644-658.

Witt, M.D., Junginger, M., Lensink, S., Londo, M., & Faaij, A. (2010). Competition between biofuels: Modeling technological learning and cost reductions over time. *Biomass and Bioenergy*, *34*, 203-217.

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