Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy

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Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting, Pittsburgh, Pennsylvania, July 24-26, 2011.

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Abstract

This paper examines the extensive and intensive margin changes in land use in the U.S. likely to be induced by biofuel policies and the implications of these policies for GHG emissions over the 2007-2022 period. The policies considered here include the Renewable Fuel Standard (RFS) by itself as well as combined with current biofuel tax credits or a carbon price policy. We use a dynamic, spatial, multi-market equilibrium model, Biofuel and Environmental Policy Analysis Model (BEPAM), to endogenously determine the effects of these policies on cropland allocation, food and fuel prices, and the mix of first and second-generation biofuels. We find that the increase in crop prices under the RFS is likely to be less than 20% in most cases and this increase is much smaller when the RFS is accompanied by volumetric subsidies or a carbon price policy since these policies induce a switch away from corn ethanol to cellulosic biofuels. The impact of the RFS on GHG emissions reduction in the U.S. is fairly modest in size but increases when the RFS is accompanied by volumetric subsidies or a carbon price policy. However, domestic savings in GHG emissions achieved by the RFS can be severely eroded by the indirect land use changes and the rebound effect on global gasoline consumption. The net reductions in global GHG emissions are largest when the RFS is accompanied by a carbon price policy.

Land Use and Greenhouse Gas Implications of Biofuels: Role of Technology and Policy

There is considerable policy support for biofuels in the U.S. as a means for reducing dependence on foreign oil, mitigating climate change, and stimulating rural economic development. These policies can have significant direct and indirect implications for land use in the U.S. and elsewhere by diverting land from existing uses to biofuel production and by affecting crop prices and the profitability of alternative land uses. The extent to which this will be the case will depend critically on the nature of the policy support provided and the technological pathways that can be developed successfully. Technology development in the biofuel industry and global land use changes together determine the greenhouse gas (GHG) reduction achieved by biofuels.

The first generation biofuels used as a transportation fuel in the U.S. are those produced domestically from food based crops, corn and soybeans, in the US and from sugarcane in Brazil. Concerns about their negative impacts on food prices have led to increased emphasis on the development of second generation biofuels produced from non-food based cellulosic biomass feedstocks. While technology for producing biofuel from cellulosic feedstocks is not yet commercially available, several possible biomass feedstocks and conversion technologies are currently under research and development and expected to be available over the next two decades (EIA 2010; Hamelinck and Faaij 2006). Biomass as feedstock for cellulosic biofuels can be obtained from crop and forest residues, dedicated energy crops, and short-rotation woody crops. These feedstocks differ considerably in their yields, land use requirements, and GHG intensity (Khanna et al. forthcoming).

So far, with the exception of sugarcane ethanol in Brazil, biofuel is not economically viable and has been produced only with considerable policy support. Policy incentives to induce cellulosic biofuel production in the U.S. include the Renewable Fuel Standard (RFS), higher tax credits for cellulosic biofuels than for corn ethanol, and an import tariff to protect domestic production from the competition of the more mature sugarcane ethanol industry in Brazil. These policies will lead to changes in land use both at the intensive margin by altering crop mixes and at the extensive margin by bringing non-cropland into bioenergy feedstock production and have implications for food and fuel prices and GHG emissions. The magnitude of these land use effects will depend on a number of factors including the mix of feedstocks induced by policy incentives, anticipated rates of crop productivity growth, production costs of cellulosic biofuels, the ease of land use conversion and the productivity of non-cropland that is brought into crop production.

The purpose of this paper is to explore the implications of biofuels for land use and GHG emissions under a variety of biofuel policy and technology scenarios and to identify the key factors that shape these outcomes. The policies considered here include the biofuel mandate by itself as well as combined with existing biofuel tax credits. Since these tax credits are authorized only through the end of 2012, we also consider the case of the RFS accompanied by a carbon price instead of tax credits. More specifically, this paper analyzes the effect of these policies on land use change and the specific geographical locations and types of land likely to undergo changes in cropping patterns. We also examine the effects of demand side conditions that influence the mix of biofuels likely to be produced and their competitiveness with fossil fuels as well as the effects of supply side conditions, including land availability and crop productivity and costs, to determine the amount and type of land likely to be used for biofuel production.

In assessing the impact of biofuels on GHG emissions, it is important not only to compare the GHG intensity of biofuels relative to gasoline but to also examine the implications of market-mediated effects of biofuel production on GHG emissions in the agricultural and fuel sectors because it will affect food and fuel prices. Two of these effects that have raised particular concern are the rebound effect and the indirect land use change (ILUC) effect due to biofuels (see review in Khanna, Crago and Black 2011). The rebound effect is expected to arise since the U.S. is a large importer of oil and a reduction in domestic demand for liquid fossil fuels will lower the world price of oil and thus increase the demand for oil in the rest of the world. Estimates of this global rebound effect of biofuels range from 29% to 70% (Stoft 2010). This will offset some of the reduction in demand for gasoline that would otherwise have been displaced by biofuels and reduce the GHG savings achieved by biofuels. The magnitude of the rebound effect of biofuel production will differ across policies, depending on their impact on fuel prices. A carbon price policy accompanying the biofuel mandate could offset some or all of the fuel price reduction due to the mandate and reduce the size of the rebound effect as compared to a biofuel mandate accompanied by tax credits.

The ILUC effect is expected to arise as the increase in crop prices in the world markets induces crop acreage expansion on native vegetation and forested land in other regions of the world which releases the carbon stored in these ecosystems. Estimates of the ILUC effect of biofuels differ across studies, across feedstocks and across modeling assumptions within a study (see review in Khanna, Lasco and Black 2011; Plevin et al. 2010)[1]. Our purpose here is not to

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[1] Estimates of the CO_2 intensity of corn ethanol not including ILUC are 60-65 g CO_2 per Mega-joule (MJ) CARB. 2009. *Proposed Regulation to Implement the Low Carbon Fuel Standard Volume I.* California Environmental Protection Agency Air Resouces Board : http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol1.pdf.. Liska et al. (2009) estimate this intensity to lie between 31-76 g CO_2 per MJ. Plevin et al. Plevin, R. J., M. O'Hare, A. D. Jones, M. S. Torn, and H. K. Gibbs. 2010. "Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated." *ENVIRONMENTAL SCIENCE & TECHNOLOGY*: estimate the value of the ILUC related GHG intensity of corn ethanol within a 95% central interval to lie between 21 and 142 g CO_2 per MJ. (CARB, 2009); Hertel et al.Hertel, T. W., A. A. Golub, A. D. Jones, M. O'Hare, R. J. Plevin, and D. M. Kammen. 2010. "Effects of US Maize Ethanol on Global Land Use and Greenhouse Gas Emissions: Estimating Marketmediated Responses." *BioScience* 60 (3): 223-231. estimate it to be 27g while Searchinger et al. Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." *Science* 319 (5867): 1238-1240. estimate it to be 100g CO_2 MJ while the California Air Resources Board (CARB) estimates it to be 30 g CO_2 per MJ CARB. 2009. *Proposed Regulation to*

determine the magnitude of the ILUC effect of biofuel production; instead we seek to explore the sensitivity of the GHG mitigation effects of biofuel policies to various magnitudes of the ILUC effect estimated by other studies. We examine the implications of these ILUC effects under various policy, technology and market scenarios for the potential for GHG mitigation through biofuel production.

Our analysis is conducted using a dynamic, multi-market equilibrium, nonlinear mathematical programming model, Biofuel and Environmental Policy Analysis Model (BEPAM) (Chen et al. 2011). The model simulates the transportation and agricultural sectors in the U.S. and considers trade in gasoline, biofuels and agricultural commodities with the rest of the world. It endogenously determines the effects of various policies on land allocation, fuel mix, and prices in markets for fuel, biofuel, food/feed crops and livestock and on GHG emissions in the U.S. at annual time scales over the period 2010-2035. Among the 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 residues, forest residues and dedicated energy crops, namely perennial grasses such as switchgrass and miscanthus.

The model includes a detailed representation of the fuel sector with demand for various types of vehicles driving demand for liquid fossil fuels and biofuels subject to technological constraints on blending the two. It also explicitly models several technological pathways for producing biofuels and enables us to examine the sensitivity of economic and GHG outcomes to

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Implement the Low Carbon Fuel Standard Volume I. California Environmental Protection Agency Air Resouces Board : http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol1.pdf.. The range for the ILUC related GHG intensity of switchgrass is equally wide-ranging from 14.2 g CO_2 per MJ EPA. 2010. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis.* US Environmental Protection Agency. to 100 g CO_2 per MJ Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." *Science* 319 (5867): 1238-1240.

alternative scenarios for innovation in the future. The representation of the agricultural sector incorporates heterogeneity in land availability, productivity and returns under alternative management activities (rotation, tillage and irrigation practices) by using geographically-specific information at a crop reporting district (CRD) level. Life-cycle GHG emissions associated with each of the biofuel pathways included in the model are assessed to quantify the GHG mitigation effects of biofuel production.

There are several static partial and computable general equilibrium models examining the implications of the RFS-induced first generation biofuel production in the U.S. for food/feed prices and land use (see review in Chen et al. 2011; Khanna, Crago and Black 2011). The GTAP model has been applied to examine the direct and indirect land use changes of the mandate for corn ethanol in the U.S. (Hertel et al. 2010; Hertel, Tyner and Birur 2010). These analyses show a very modest increase in cropland (by about 1%) in the U.S. with much of the increase in land under biofuel feedstocks coming from a reduction in land under other agricultural crops and some from reduction in land under pastureland and accessible forest land. They find that biofuel production would reduce the world price of oil and improve the terms of trade for the U.S., offsetting some of the efficiency loss of the mandate. They also assess the ILUC effect of corn ethanol production, but they do not examine the magnitude of the rebound effect and its implications for GHG emissions.

Among the partial (multi-market) equilibrium models, the FAPRI model simulates the impact of corn ethanol production on the food and feed prices in the agricultural and livestock sectors (Elobeid et al. 2007). It has also been applied to estimate country-specific cropland acreage multipliers as a result of expansion of corn ethanol production in the U.S. (Fabiosa et al. 2010). Another static partial equilibrium model of the U.S. agricultural sector, AGMOD (Ferris and Joshi 2009), finds that the RFS could be met by potential crop yield increases and a decline in land under the Conservation Reserve Program and cropland pasture. One of the few multi-market models that includes both first and second generation biofuels and examines the implications of the RFS over the 2007-2022 period using a dynamic optimization framework is FASOM (Adams et al. 2005; Beach and McCarl 2010), which also suggests a very modest impact of the RFS on land use with some increases in aggregate cropland and pasture land accompanied by a reduction in land under forests.

These studies examine the effect of biofuels on GHG emissions from the agricultural sector but do not examine the overall implications of biofuels for GHG emissions from the fuel sector. These studies differ in the manner in which they model the demand for biofuels and incorporate the feedback effect of biofuels on oil prices. While GTAP assumes that biofuels and oil are imperfectly substitutable with a constant elasticity of substitution, the FAPRI and FASOM models assume that the two are perfect substitutes. The FAPRI model also assumes a fixed gasoline price, while the GTAP and FASOM models consider a price responsive supply of gasoline.

BEPAM differs from the other partial equilibrium models in that it integrates the agricultural and fuel sectors and endogenously determines the mix of feedstocks used to produce biofuels and the share of first generation and second generation biofuels. Instead of treating biofuels as either a perfect substitute for gasoline or an imperfect substitute with a constant elasticity of substitution, it explicitly derives the demand for alternative fuels from projected demands for alternative types of gasoline and diesel vehicles with consideration of their technological limits to fuel substitution. These technological limits to substitution change over time as the vehicle fleet structure changes to allow higher substitutability among fuels over time.

Moreover, by incorporating separate supply functions for domestically produced gasoline and imported gasoline, BEPAM determines the imports and the price of gasoline in the U.S. endogenously; this allows biofuel production in the U.S. to affect the world price of gasoline and its feedback effect to affect the demand for biofuels in the U.S. Other distinguishing features of BEPAM include its finer spatial resolution and use of a biophysical crop yield simulation model to simulate yields of switchgrass and miscanthus. BEPAM also allows land use changes across crops to be price-responsive rather than determined entirely by historically observed crop mixes (as in FASOM). Moreover, it uses a rolling horizon approach to model the dynamics of a landowner’s decision to allocate land among crops, some of which are long lived perennials whose costs and yields differ with the age of the crop. The model also allows landowners to update their price expectations and land availability annually as they make decisions for the next ten years. Given the uncertainties about market and technological conditions, we examine the sensitivity of the land use and GHG outcomes of biofuel policies to various parameter assumptions and provide an assessment of key factors likely to determine the effect of these uncertainties.

II. Model Description

BEPAM is a multi-market, multi-period, price-endogenous, nonlinear mathematical programming model that simulates the U.S. agricultural and fuel sectors and the formation of market equilibrium in the commodity and fuel markets including trade with the rest of the world. Market equilibrium is simulated by maximizing consumers’ and producers’ surpluses in the fuel and agricultural sectors subject to various material balances and technological constraints underlying commodity production and consumption within a dynamic framework. This model determines several endogenous variables simultaneously, including vehicle kilometers traveled (VKT), fuel and biofuel consumption, domestic production and imports of liquid fossil fuels, imports of sugarcane ethanol, mix of biofuels and the allocation of land among different food and fuel crops and livestock over a given time horizon (2007-2022 in this case).

Transportation Sector:

This sector includes downward sloping demand curves for VKT with three types of vehicles that use gasoline or ethanol as fuel, including conventional vehicles (CVs), flex fuel vehicles (FFVs) and gasoline-hybrid vehicles (HVs). It also includes a downward sloping demand curve for VKT by all on-road transport vehicles, heavy duty trucks and light duty vehicles that use diesel and diesel substitutes as fuel. These demand curves for VKT with each type of vehicle shift to the right over time as projected by the Annual Energy Outlook (AEO) (EIA 2010).The demand for VKT by each of these types of vehicles endogenously generates demands for liquid fossil fuels and biofuels given the energy content of alternative fuels, the fuel economy of each vehicle type, and biofuel blend limits for each type of vehicle.

We include upward sloping supply curves for domestic gasoline production and for gasoline supply from the rest of the world (ROW). The excess supply of gasoline to the U.S. at various prices is derived as the difference between the ROW gasoline demand and supply. Since diesel fuel is primarily produced domestically, we include an upward sloping supply curve to represent its marginal costs of domestic production and price responsiveness.

The biofuel sector includes several first and second generation biofuels; the former consists of domestically produced corn ethanol and soy diesel as well as imported sugarcane ethanol while the latter consists of biofuels produced from cellulosic biomass from crop and forest residues, miscanthus and switchgrass. Biomass from these feedstocks can be converted to either lignocellulosic ethanol to be blended with gasoline or to biomass to liquids (BTL), a Fischer-Tropsch process derived diesel fuel to be blended with petroleum diesel.

While advanced biofuels are currently too expensive to produce at a commercial scale, these costs are expected to decline in the future with technological innovation and learning by doing. Studies differ in the approach they take for modeling the reductions in conversion costs for biofuels over time. In its impact analysis of the RFS, the EPA (2010) specifies future cost levels for lignocellulosic ethanol ex-ante. This approach ignores demand driven market dynamics and the empirically observed relationship between technological learning and related cost reductions and the extent to which a technology is utilized. This relationship between technological learning and related cost reductions has been quantified by several studies using the experience curve approach, which relates the cost decline to a constant factor with each doubling of cumulative units produced (Witt et al. 2010). This relationship is expressed as $C_{cum,i} = C_{0,i} Cum^{b_i}$, where C_0 is the cost of the first unit of production, *Cum* is the cumulative production and *b* is the experience index representing the rate at which costs decline for every doubling of cumulative production. The subscript *i* indicates that this relationship differs across different types of biofuels. The costs of biofuel processing are considered fixed at a point in time in endogenously determining the optimal mix of biofuels to meet the biofuel mandate. However, production in each period adds to the cumulative level of production and lowers processing costs for the next period. Although processing costs of biofuels would become lower than in the previous period due to the increase in cumulative production, the implicit marginal cost curve of producing biofuel from a particular feedstock is upward-sloping over a given time period. This is because as the biofuel production increases, it intensifies the competition for cropland and raises land rents.

We model the RFS as a consumption mandate that requires fuel blenders to blend a fixed quantity of biofuels with liquid fossil fuels and thus imposes a fixed cost on blenders. With biofuels (in energy equivalent units) being perfect substitutes for fossil fuels and assuming that consumers have the choice of the blend to consume, fossil fuels and biofuels have to be priced the same in energy equivalent terms. Since the RFS will lower the demand for fossil fuels, it will lower the price of fossil fuels and thus the price at which biofuels can be sold, thereby lowering the cost per km of VKT (Ando, Khanna and Taheripour 2010; Chen 2010). However, the marginal cost of producing biofuels could be higher than the price that fuel consumers are willing to pay; thus, the gap between the marginal cost of producing biofuels and the consumer price of biofuels (times the quantity of biofuels consumed) would be borne by blenders and represent the fixed cost of the mandate for them.

The provision of tax credits to accompany the RFS could lead to the mandate being exceeded; in that case it will further decrease the price of the blended fuel by increasing the displacement of liquid fossil fuels and lead to an increase in VKT (Khanna, Ando and Taheripour 2008). However, if the mandate continues to bind, the tax credits will simply represent a transfer of surplus from tax payers to blenders, leading to a smaller surplus loss for fuel blenders relative to a mandate alone. In contrast to tax credits, a carbon price policy that accompanies the RFS will offset at least a part of the reduction in fossil fuel prices and raise the cost of the blended fuel, thereby reducing the demand for VKT as compared to that under the RFS alone.[2]

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[2] This representation of the RFS differs from that in de Gorter and Just (2009) who analyze a blend mandate that requires biofuels to be blended in a given proportion with fossil fuels. With a blend mandate the consumer price of the blended fuel is a weighted average of the price of gasoline and biofuel, with weights depending on the share of biofuels in the blend. The effect of the blend mandate on the price of the blended fuel is, therefore, theoretically ambiguous; the mandate increases the price of biofuel, but it lowers gasoline consumption and thus its price.

Agricultural Sector:

The agricultural sector in BEPAM includes conventional crops, livestock and bioenergy crops, as well as co-products from the production of corn ethanol and soy diesel. Crops can be produced using alternative tillage, rotation, and irrigation practices. The model incorporates spatial heterogeneity in crop and livestock production activities, where crop production costs, yields and resource endowments are specified differently for each region and each crop. The spatial decision unit is a CRD, and there are 295 CRDs in 41 of the contiguous U.S. states in five major regions[3]. As a result of this heterogeneity in costs and land availability in each CRD, the implicit supply curves for crops are upward sloping. The costs of land (land rents) increase over time as demand for land for food crop and biofuel feedstock production increases.

A rolling horizon approach is used to allocate land to annual crops and perennials over a 10 year planning period. After solving optimal choices for the first planning horizon (2007-2016), producers take crop prices and cumulative biofuel production for the first year (2007) of the horizon from the realized market equilibrium to form expectations about availability of cropland, crop yields and the cost of conversion of feedstocks to biofuels for the next 10 years (2008-2017). The model is then re-run to maximize the discounted sum of producer surplus for the subsequent 10 years and determine crop and biofuel production choices over this subsequent 10 year period. This approach enables the model to take into account the perennial nature of the energy crops, whose yields and costs of production differ over their life-cycle. This framework also recognizes the one to two year lag between planting of energy crops and the incurring of crop establishment costs before harvestable yield become available (see Chen et al. 2011).

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[3] Western region includes Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming; Plains includes Nebraska, North Dakota, Oklahoma, South Dakota, Texas and Kansas; Midwest includes Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin; South includes Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi and South Carolina; Atlantic includes Kentucky, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Tennessee, Virginia, and West Virginia.

Equilibrium prices in markets for crop and livestock commodities are determined by specifying domestic and export demand/import supply functions for individual commodities, including both primary and processed crop and livestock products. In the crop and livestock markets, primary crop and livestock commodities are either domestically consumed or traded with the rest of the world (exported or imported), processed, or directly fed to various animal categories. Domestic and export demands and import supplies are incorporated by using linear demand/supply functions. The commodity demand functions and export demand functions for crops and processed commodities are shifted upward over time at exogenously specified rates.

In the livestock sector, we consider several types of meat (chicken, turkey, lamb, beef, and pork), wool, dairy, and eggs. The livestock and crop sectors are linked to each other in two ways. First, the crop sector provides feed for the production of livestock animals. Second, beef and dairy cattle require grazing land, and compete for land with crop production in each region. Thus, the supply of beef is restricted by the number of cattle which in turn depends on the amount of grazing land available at regional level. We model the supply of other livestock commodities, including chicken, turkey, lamb, pork, wool, diary and eggs, at the national level, and their supply is constrained by their historical quantities.

Livestock production requires nutrition in terms of protein and calories provided by feed crops and byproducts of crop processing, such as soymeal and Distiller's Dried Grains with Solubles (DDGS) (a byproduct of corn ethanol production). These livestock feeds (feed crops, soymeal, and DDGS) differ not only in terms of the fraction of dry matter, but also in their content of protein and calories. BEPAM uses the dry matter and nutrient content per unit of livestock feed to find the least cost feed rations for each type of livestock. In addition, we impose upper bounds for the share of DDGS in total feed consumption for each livestock category as in Babcock et al. (2008).

The model uses 'historical' and 'synthetic crop mixes' when modeling farms' planting decisions to avoid extreme specialization in regional land use and crop production. To accommodate planting new bioenergy crops and unprecedented changes in crop prices we use synthetic (hypothetical) mixes to offer increased planting flexibility beyond the observed levels and allow land uses that might occur in response to the projected expansion in the biofuels industry and related increases in corn and cellulosic biomass production. Each synthetic mix represents a potential crop pattern generated by using estimated own and cross price crop acreage elasticities and considering a set of price vectors where crop prices vary systematically. Crop yields are assumed to grow over time at an exogenously given trend rate and to be responsive to crop prices, based on econometrically estimated trend rates of growth and price responsiveness of crop yields in the U.S. (see Chen et al. 2011). Following Hertel et al. (2010) and for lack of other data, we assume that marginal lands have a crop productivity that is 66% of that of the average cropland. We examine the sensitivity of our model to restrictions in the ease of conversion of land across uses and to the assumed ratio of marginal to average productivity of cropland.

The model includes several types of cropland and land that is idle or marginal for each CRD. Cropland availability in each CRD changes in response to crop prices. Idle land and cropland pasture are assumed to move into cropland and back into an idle state. They can also be converted for the production of energy crops after incurring a conversion cost. Other lands, including pasture land and forestland pasture are fixed at 2007 levels while land enrolled in the Conservation Reserve Program (CRP) is fixed at levels authorized by the Farm Bill of 2008.

While yields of bioenergy crops are assumed to be the same on marginal land as on regular cropland there is a conversion cost to the use of idle land/cropland pasture for bioenergy crop production. In the absence of an empirically based estimate of the ease of conversion of marginal land for perennial grass production, we assume a CRD-specific conversion cost equal to the returns the land would obtain from producing the least profitable annual crop in the CRD. This ensures consistency with the underlying assumption of equilibrium in the land market, in which all land with non-negative profits from annual crop production is utilized for annual crop production. As annual crop prices increase, the cost of conversion increases; the "supply curve" for idle marginal land is, therefore, upward sloping. We impose a limit of 25% on the amount of land in a CRD that can be converted to perennial grasses due to concerns about the impact of monocultures of perennial grasses on biodiversity or sub-surface water flows. We examine the sensitivity of model results to this assumption by considering two alternative limits of 10% and 50%. The endogenous variables determined by the model for each year of the 2007-2022 planning horizon include: (1) commodity and fuel prices; (2) production, consumption, export and import quantities of crop and livestock commodities; (3) land allocations and choice of practices for producing row crops and perennial crops (namely, rotation, tillage and irrigation options) for each CRD and (4) the annual mix of feedstocks for biofuel production, domestic production and imports of liquid fossil fuels, consumption of VKT and GHG emissions.

III. Data and Assumptions

We include four vehicle types, i.e., conventional gasoline (CVs), ethanol flex (FVs), gasoline and electric hybrid (HVs), and diesel vehicles (DVs). Demands for vehicle kilometers traveled (VKT) for each of the four vehicle types from 2007 to 2030 are obtained from EIA (2010a). Gasoline, diesel, ethanol and biodiesel consumed by on-road vehicles in 2007 are obtained from Davis et al. (2010). Retail fuel prices, markups, taxes and subsidies are obtained from EIA (2010a). We assume demand elasticities for VKT as -0.2 (Parry and Small 2005). We calibrate these VKT demand curves for year 2007 using a linear functional form and then shift the demand curves outwards based on the EIA VKT projections for the 2007-2022 period.

Fuel economy in terms of kilometers per liter of fuel for each vehicle type is derived from EIA (2010a). Fuel demands by vehicles are constrained by biofuel blend limits that are technologically determined and specific to fuel and vehicle types, in addition to a minimum ethanol blend for all gasoline to meet the oxygenate additive requirement (Meyer and Thompson 2010). The short-run supply curves of gasoline in the U.S. and demand and supply curves for gasoline for the rest of the world (ROW) are assumed to be linear and calibrated for 2007 using data on fuel consumption and production in the U.S. and for the ROW (EIA 2010b). The short-run supply of domestic gasoline in the US is assumed to be linear, with an elasticity of 0.049 at $35 per barrel (Greene and Tishchishyna 2000). We assume a similar price responsiveness for the domestic supply curve of diesel. These estimates are consistent with the estimate obtained by Gately (2004) and those obtained from a review of the literature (Greene and Ahmad 2005; Huntington 1991). The exports of gasoline from the ROW to the U.S. and its price responsiveness are determined by specifying demand and supply functions for gasoline for the ROW. We assume a value of -0.26 for the elasticity of demand for gasoline in the ROW (based on a review of the literature by Hamilton (2009). There is considerably uncertainty about the estimate of the elasticity of gasoline supply for the ROW. We assume a short- run price elasticity of supply of gasoline of 0.2 (following the review of literature in Leiby (2008)). We also consider the case where the short run elasticity of supply of gasoline is more inelastic and similar to that for the U.S. of 0.049.

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 a county level for each crop using data and methods described in Chen et al. (2011) while the costs of land are endogenously determined by shadow price of the land constraint in the model. The costs of converting feedstock to biofuel are estimated using an experience curve approach. The initial individual biofuel conversion costs are obtained from various sources including EPA (2010), Swanson et al. (2010), and Crago et al.(2010). The conversion efficiencies (yield of biofuel per metric ton of feedstock) are exogenously fixed and based on the estimates in GREET 1.8c for corn ethanol and Wallace et al. (2005) for cellulosic ethanol. The value of the index b in the experience curve defined above is assumed to be -0.07 for cellulosic ethanol, BTL and corn ethanol, and -0.03 for biodiesel produced from vegetable oils (Witt et al. 2010). For sugarcane ethanol we assume that the total costs of production (including feedstock cost) decline at a value of b, -0.32, and an exogenously specified rate of growth for sugarcane ethanol production, 8% (van den Wall Bake et al. 2009). The parameters for first and second generation ethanol are obtained from EPA (2010), for BTL from de Witt et al. (2010) and for sugarcane ethanol from Van Den Wall Bake et al. (2009). We use U.S. ethanol retail prices and imports from Brazil and Caribbean countries in 2007 as well as an assumed elasticity of the excess supply of ethanol import of 2.7 to calibrate the sugarcane ethanol import supply curve for the U.S (Lee and Sumner 2009).

Biodiesel pathways include soybean oil biodiesel, DDGS corn oil biodiesel, and renewable diesel from waste grease, and various cellulosic biomass feedstocks. Feedstock costs for soybean oil diesel are assumed to be the endogenously determined market price for soybean oil. The conversion rate from vegetable oil or waste grease to biodiesel is obtained from

FASOM (Beach and McCarl 2010). The conversion coefficient of DDGS to corn oil and the cost of extracting oil from DDGS are based on a report by Business Wire (2006). The price of DDGS oil and the adoption rate of DDGS oil diesel technology over time are from FASOM. The cost and annual production of waste grease diesel is exogenously given as in Beach and McCarl (2010). The conversion rates of cellulosic feedstocks to BTL and lignocellulosic ethanol are obtained from EPA (2010).

The simulation model uses crop reporting district (CRD) specific data on crops, livestock, biofuel feedstocks, and land availability. We estimate the rotation, tillage and irrigation specific costs of production in 2007 prices for 15 row crops and three perennial grasses at county level and aggregate them to the CRD level for computational ease. Data on crop and livestock production, prices, consumption, exports and imports as well as land availability and the conversion rates from primary commodities to secondary (or processed) commodities are obtained primarily from USDA/NASS (2009). Elasticity and demand/supply shift parameters for agricultural commodities are assembled from a number of sources described in Chen et al. (2011). The conversion costs from primary to secondary commodities as well as nutrition requirements and costs of production for each livestock category are obtained from Adams et al. (2005). Nutrient contents of livestock feeds are obtained from NRC (1998) and Akayezu et al. (1988) while DDGS prices are estimated based on Ellinger (2008). The responsiveness of total cropland to crop prices and corn and soybeans acres to their own and cross-prices are obtained from Huang and Khanna (2010).

Dedicated energy crops included in the model are miscanthus and switchgrass as numerous studies suggest that these two perennials are among the best choices for high yield potential, adaptability to a wide range of growing conditions and environmental benefits in the

U.S. and Europe (Jain et al. 2010). In the absence of long term observed yields for miscanthus and limited data for switchgrass, we use a crop productivity model MISCANMOD to simulate their potential yields. These estimated yields are further adjusted to account for higher yields of the lowland varieties, as described in Chen et al. (2011). We assume that the simulated yields of these energy crops represent the technical potential under experimental conditions; actual yields likely to be obtained by individual landowners are expected to be 20% lower than this potential (as found to be the case for other crops by Lobell, Cassman and Field 2009). The methods for estimating the delivered costs of miscanthus and switchgrass are described in Jain et al. (2010).

Costs of producing row crops and alfalfa are obtained from the crop budgets complied for each state by state extension services. Applications rates for fertilizer are assumed to remain constant over time regardless of yield increases (Cassman, Dobermann and Walters 2002; Cassman et al. 2003; Fixen and West 2002). Corn stover and wheat straw yields are estimated based on grain-to-residue ratios and residue collection rates under different tillage in the literature (Graham, Nelson and Sheehan 2007; Sheehan et al. 2003; Wilcke and Wyatt 2002). The cost of collecting stover and straw entails an additional fertilizer cost needed to replace the loss of nutrients and soil organic matter due to residue removal (Sheehan et al. 2003; Wortmann et al. 2008). The costs of mowing, raking, baling, staging and storage of crop residues are based on state-specific hay harvesting budgets.

Life cycle GHG emissions for gasoline and diesel are obtained from the EIA Vision model and the GHG intensity of petroleum fuels increases over time as the share of high carbon crude oil increases (Rubin 2010). Estimates of the life-cycle GHG emissions for the biofuel pathways consist of emissions for the agricultural phase and for the biofuel refinery, distribution and use. The emissions during the agricultural phase include emissions from agricultural input use such as fertilizer, chemicals, fuels and machinery. These input use data are obtained from region specific crop budgets while the life-cycle GHG emission factors for these inputs as well as emissions from biofuel conversion, distribution and use are obtained from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET 1.8c). For cellulosic ethanol and biodiesel, the life cycle carbon intensity of the biofuel conversion process are obtained from CARB (2009) or EPA (2010). We assume an average rate of soil carbon sequestration per dry metric ton of biomass produced for switchgrass and miscanthus from Anderson-Teixeira et al. (2009) and for conservation tillage from Adler et al. (2007). For estimating the impact of ILUC related emissions due to biofuels we take the central estimates for the ILUC related GHG intensity of biofuel from each of the feedstocks considered here obtained from EPA (2010) and add these to the direct GHG intensity of these biofuels. Since the analysis by EPA (2010) does not consider miscanthus as a feedstock and therefore does not provide an ILUC related GHG intensity for miscanthus, we assume this is the same as for switchgrass. Additionally, the ILUC effect of a particular biofuel type is expected to be dependent on the mix of policies because that will influence the mix of biofuels and its impact on land use and commodity prices. In the absence of policy specific ILUC effects, we use the EPA (2010) estimates to provide an order of magnitude for the ILUC effect on the GHG mitigation potential of biofuels. The ILUC estimates used here are 30.33 g CO_2/MJ for corn ethanol, 40.76 g CO_2/MJ for soybean oil diesel, 14.22 g CO_2/MJ for cellulosic biofuels, and 3.79 g CO_2/MJ for sugarcane ethanol. Since there is a wide range for the ILUC related GHG intensity of biofuels, we also consider the case where these estimates are 100% larger.

VI. Results

We first validate the simulation model assuming existing fuel taxes, 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 the base year (2007). A minimum ethanol consumption mandate is imposed as specified by the EISA RFS for 2007. As shown in Table 1, the differences between model results and the observed land use allocations and commodity prices for major crops (corn, soybeans, wheat, and sorghum) are typically less than 10%. Fuel prices and consumption are also simulated well, within 5% deviation from the observed values with the exception for corn ethanol price and ethanol consumption that are 16% and -6%, respectively.

We examine the effects of three policy scenarios on the agricultural and fuel sectors, which include various mixes of policies accompanying the RFS. The volumes of second generation biofuels as mandated by the RFS in the Energy Independence and Security Act (EISA) of 2007 are considered unlikely to be achieved according to the AEO (EIA 2010). A full implementation of the RFS as required by EISA would have implied cellulosic biofuel production starting in 2010 and total renewable fuel production being at least 136 B liters in 2022. Instead, we use the AEO projections for the annual volumes of first generation biofuels (corn ethanol, sugarcane ethanol imports, biodiesel produced from vegetable oils) and second generation biofuels (cellulosic ethanol and BTL) to set the achievable biofuel mandate for the period 2007-2022. This implies an upper limit of 57 billion liters of annual production for corn ethanol in 2015 and beyond. We assume that commercial production of cellulosic biofuels will be feasible in 2015, and that total renewable fuel (first and second generation biofuels) production will be at least 94 billion liters in 2022. We endogenously solve for the mix of first and second generation biofuels and the mix of feedstocks used subject to these constraints. Scenario (a) considers the RFS following AEO projections. Scenario (b) considers the RFS in (a) with the volumetric tax credits for biofuels. We examine the potential of the provision of tax credits to stimulate additional biofuel production and bring production levels close to those mandated by EISA. Scenario (c) includes the AEO RFS accompanied by a carbon tax on all fuels. The carbon tax varies over time and is based on the carbon allowance prices under the cap-and-trade provisions of the American Clean Energy and Security (ACES) Act as projected by the EIA (2009). In their basic case[4], the allowance price is \$20/Mg CO2e in 2010 and gradually increases to \$39/Mg CO2e in 2022. We compare results under these biofuel policies to those under a business-as usual (BAU) scenario in 2022. The BAU scenario is defined as one without any biofuel or climate change mitigation policy. In all scenarios considered here, we include a fuel tax on liquid fossil fuels and biofuels, which is set at \$0.10 per liter for gasoline and ethanol and \$0.12 per liter for diesel, BTL and biodiesel. Results on the impact of these policies on the allocation of cropland and food prices are presented in Table 2, while Table 3 shows the results for fuel prices and consumption in 2022, and cumulative GHG emissions over the 2007-2022 period.

A. Business-As-Usual (BAU) Scenario

In the absence of any government intervention in biofuel markets, we find that the demand for total cropland decreases by 0.4% from 122.1 million hectares in 2007 to 121.7 million hectares in 2022. This decrease can be attributed to an increase in crop productivity that results in a reduction in corn and soybeans acreages by 6% (1.8 million hectares) and 1% (0.2 million hectares), respectively, despite an increase in demand for these crops. Corn and soybeans prices decrease by 10% and 2% due to 17% and 9% yield increases, respectively, over the 2007-2022. Moreover, the increase in corn yields reduces the cropland allocated to corn ethanol in 2022 by

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[4] Among the six cases examined in EIA (2009), the basic case is considered the most realistic scenario.

20% (0.8 million hectares) while the production of corn ethanol remains stable over the 2007-2022 period under the BAU. In the fuel sector, we do not observe any second generation biofuels production due to their high costs of production. In comparison to 2007, the increase in VKT raises gasoline and diesel prices in 2022 by 19% and 5%, respectively.

B. The RFS

The amount of corn ethanol that can be used to comply with the RFS is capped at 57 billion liters from 2015 and beyond. Thus, corn ethanol could constitute a maximum of 61% of the total biofuel production in 2022 (94 billion liters), while the remaining portion can be met by sugarcane ethanol, cellulosic biofuels, and biodiesel. Given the assumed rate of the reduction in processing costs of cellulosic biofuels, we find that over time second generation biofuels would become increasingly competitive and this would reduce the volume of the first generation biofuels to 36 billion liters with the production of second generation biofuels increasing to 58 billion liters, primarily in the form of lignocellulosic ethanol. High processing costs of BTL biodiesel preclude its production over the time horizon considered here. Of the 36 billion liters, about 83% (30 billion liters) are produced from corn starch while the rest consists of sugarcane ethanol (3.5 billion liters) and biodiesel produced from vegetable oils. The volume of first generation biofuels is 100% higher as compared to the BAU scenario in 2022.

The RFS-induced demand for biofuel requires an additional 8.6 million hectares for biofuel production (including land under energy crops and land for corn ethanol production) compared to the BAU scenario in 2022. This represents 6.8% of total cropland of 125 million hectares in 2022. Of this, changes at the extensive margin lead to 4 million hectares of net conversion of idle/crop-pasture land to crop production (most of this is for energy crop production) and the remaining 4.6 million hectares (representing changes at the intensive margin) are released from other crops. These changes at the extensive margin more than offset the reduction in cropland under the BAU over the 2007-2022 period, leading to a net increase in total land under crop production by 3% (4 million hectares) relative to the BAU scenario in 2022. Energy crops will be planted on 5.1 million hectares, of which only 0.8 million hectares is diverted from cropland and the rest is converted from land currently or likely to become idle/cropland pasture. Crop residues (corn stover and wheat straw) will be harvested from 6.8 million hectares of corn and wheat land in 2022. Corn ethanol production requires an additional 3.5 million hectares relative to the BAU scenario but land under corn increases only by 9% (2.8 million hectares) because higher corn prices lead to reduced domestic consumption and exports. The RFS has significant intensive margin effect, it leads to a switch in acreage from other crops to corn production and an increase in crop yields per hectare in a response to higher crop prices. Corn and soybeans prices increase by 16% and 12% in 2022 due to the reduction in cropland allocated to food production relative to the BAU. Land under corn production increases by 9%, which is largely from acreage under other crops. Due to an increase in crop prices, corn yield is a bushel per acre higher in 2022 with the RFS than in the BAU scenario.

Figure 1 shows the spatial distribution of crop residues and bioenergy crops in 2022 under alternative policy scenarios. As displayed in Figure 1(a), crop residues are harvested mainly in the Plain, Midwestern, and Western States in 2022, where the costs of corn stover and wheat straw collection are relatively low. Of the land under energy crops, about 64% is allocated to miscanthus while the rest to switchgrass; 84% of the land under energy crops was formerly idle land or cropland pasture. The production of energy crops is fairly concentrated in the Great Plains, the Midwest, and along lower reaches of the Mississippi River.

The increase in ethanol consumption reduces gasoline consumption by 8% and imports by 11%, resulting in a reduction in the gasoline price in the world market by 7% in 2022. This offsets some of the reduction in liquid fossil fuels consumption that would otherwise have been achieved by biofuels, both domestically and globally. We find the domestic rebound effect on the gasoline market is 17%, while the global rebound effect is as large as 51%. This implies that gasoline fuel displaced by a unit of biofuel is discounted by 17% domestically and 51% in the rest of the world.

Despite this domestic rebound effect, cumulative GHG emissions from the fuel and agricultural sectors in the U.S. over the 2007-2022 period (including those due to domestic land use changes but not including the ILUC effect) under the RFS are 2.2% lower than under the BAU. Inclusion of the ILUC effect at the average levels projected by the EPA (2010) decreases this reduction achieved by biofuels to 1.6%. The ILUC related GHG emissions in the RFS scenario amount to 0.05% of the cumulative GHG emissions from the agricultural and fuel sectors in the U.S. If ILUC effects are assumed to be 100% higher than the averages estimated by the EPA (2010), the reduction in GHG emissions attributed to the RFS drops to 1.1%. Inclusion of the global GHG emissions due to gasoline consumption in the ROW reduces the effects of the RFS on global GHG emissions to -0.05%.

C. Biofuel Mandate with Volumetric Tax Credit

In the presence of the biofuel mandates, the provision of tax credits for biofuels increases the production of second generation biofuels to 119 billion liters and the total production of biofuels by 30% compared to the RFS alone. This production level is still about 15 B liters (11%) lower than that mandated by EISA. However, the production of first generation biofuels shrinks to 2.6 billion liters, 93% lower than that under the RFS alone and 85% lower than under the BAU scenario in 2022. This can be attributed to the fact that the magnitude of the tax credit for cellulosic biofuels ($0.27 per liter) is much larger than that for corn ethanol ($0.12 per liter); this significantly improves the competitiveness of cellulosic biofuels relative to corn ethanol.

The tax credits increase the acreage under bioenergy crops to 10.1 million hectares, 5 million hectares higher than that under the mandate alone. The tax credits also increase the acreage from which crop residues are harvested from 13.5 million hectares under the RFS alone to 38.5 million hectares. Of the 10.1 million hectares under bioenergy crops, 4.3 million hectares are obtained at the extensive margin by converting idle land or cropland pasture, 3.2 million hectares are from the reduction in corn acreage due to lower corn ethanol production, and the rest is converted from land under soybeans, wheat, cotton, rice, sorghum, and barley. The provision of these tax credits mitigates the competition for cropland relative to the mandate alone; thus, corn and soybean prices in 2022 are 20% and 13%, respectively, lower than the prices under the RFS scenario. Even in comparison to the BAU scenario, corn and soybean prices are still 8% and 2% lower in 2022.

As compared to the RFS alone, the provision of tax credits leads to a significant expansion of acreage under bioenergy crops. As shown in Figure 1(b), the production of bioenergy crops is now profitable in upper parts of Wisconsin, Michigan, and North Dakota, as well as in lower parts of Texas, Mississippi, Alabama, and Georgia. Moreover, the tax credits result in a significant increase in land under which crop residues are harvested (180% higher relative to the RFS alone), primarily in the Midwestern, Plain, and Western states.

The increase in production of total renewable fuels further reduces gasoline consumption as compared to the RFS alone, leading to a reduction in gasoline price in 2022 by 7% relative to the

RFS alone and 10% relative to the BAU. The absolute magnitude of the domestic and global rebound effects under this scenario is larger than under the RFS alone but the quantity of additional biofuels produced under this scenario is also larger than under the RFS alone. Thus the rebound effect in percentage terms is slightly lower than under the RFS alone, down to 16% and 50%. Cumulative GHG emissions under this scenario decrease by 3.9% relative to the BAU without including ILUC related emissions and by 3.4% after including ILUC related emissions, relative to the BAU. Including the ROW gasoline emissions reduces the effect of this combined policy on GHG emissions to less than 1%.

D. The RFS with a Carbon Price Instrument

A carbon price instrument would raise the marginal costs of liquid fossil fuels and biofuels depending on carbon intensities per liter of the fuel, creating incentives to switch to the less GHG intensive fuels. By raising the costs of all fuels, it would also raise the cost of VKT and hence reduce VKT and fuel consumption. While the biofuel mandates and subsidies reduce liquid fossil fuels consumption and GHG emissions by switching to biofuels, they differ from a carbon price instrument in that they lower rather than raise the price of VKT. Compared to the RFS alone, we find that the carbon tax does not lead to additional biofuel consumption; instead it changes the mix of biofuels in favor of second generation biofuels. Because of their low carbon intensities, the production of second generation biofuels is 36% (or 21 billion liters) higher than under the RFS alone. The production of first generation biofuels now is reduced to 15 billion liters in 2022, which are 16% and 58% lower than under the BAU and the RFS alone scenarios, respectively. However, the production of second generation biofuels under the RFS with a carbon tax is 33% lower than in the case with the RFS with volumetric tax credits since carbon tax induced high fuel prices lead to an overall reduction in VKT and fuel consumption.

The total land required to meet the crop and fuel production needs is 4% (4.8 million hectares) higher than that under the BAU and marginally (0.9 million hectares) higher than under the RFS alone, mainly due to the increase in demand for bioenergy crops (9.3 million hectares) to produce second generation biofuels. Of the 9.3 million, 4.8 million hectares are converted from idle land or cropland pasture while 4.3 million hectares are obtained from land previously under row crops, such as corn, soybeans, and wheat. The reduction in corn ethanol leads to a 28% (0.8 million hectares) decrease in corn acreage allocated to corn ethanol production relative to the BAU. The acreage under which crop residues are harvested shrinks to 12.2 million hectares, 10% smaller than under the RFS alone. Corn and soybean prices are 10% and 12% respectively lower than under the RFS alone scenario, due to the increased production of high yielding energy crops. In comparison to the BAU, corn and soybean prices are 4% higher and 1% lower, respectively.

Figures 1(c) shows the regions in the U.S. where crop residues and perennial grass will be produced under the RFS with the carbon price. The carbon price policy makes more areas suitable for the production of bioenergy crops as compared to the RFS alone, because the carbon tax encourages the use of energy crops for the production of biofuels given their low carbon intensities. Similar to the RFS with subsidies, energy crops would be produced in the upper Midwest, northern Plains and southern Atlantic states, while crop residues are collected in areas similar to those under the RFS alone in general.

The carbon tax will increase gasoline and diesel prices by 5% and 13%, respectively, leading to reduced gasoline and diesel consumptions, as compared to the BAU scenario. Under the carbon tax, gasoline consumption is reduced more than the increase in biofuel production because the carbon tax not only induces the substitution of biofuels for fossil fuels but also penalizes fossil fuel consumption. As a result, the domestic rebound effect is negative since the reduction in fossil fuel consumption is larger than the increase in energy equivalent biofuel use. The carbon tax also reduces the global rebound effect to 37%, compared to that with the RFS alone. Consequently, the total U.S. GHG emissions decrease by 5% and by 4% after including the average ILUC effect related emissions as compared to the BAU, the largest reduction in GHGs achieved across scenarios considered here. The increased gasoline consumption by the ROW further offsets a part of the GHG savings by the US and global emissions decline by a little over 1%.

E. Sensitivity analysis

We examine the sensitivity of land allocation, food and fuel prices, the mix and quantity of biofuels, and GHG emissions to the key assumptions and technology and cost parameters in the model. We compute the percentage change in the outcome variables under the RFS relative to the BAU under the benchmark case described above and with each of the parameter changes considered here. In Scenarios (1) and (2) in Table 4, we change the upper limit of 25% on the amount of cropland that can be converted for perennial grass production at a CRD to 10% and 50%.. In scenarios (3)-(5), we consider scenarios that would result in high costs of production of cellulosic biofuels, including high costs of perennial grass production, high biofuel conversion costs, low crop residue collection rates, and low crop yield growth rates and marginal land productivity. More specifically, in scenario (3), we consider a case with relatively high costs of production of perennial grasses and 25% higher processing costs of cellulosic biofuels than assumed in the benchmark scenario. In Scenario 4, crop residue collection rates are lowered from

30% and 50% with conventional and conservation tillage in the benchmark scenario to 0% and 35%, respectively. In scenario (5), the rate of yield growth for major crops (corn, soybeans and wheat) are reduced by 50%, crop productivity on marginal lands is reduced from 66% to 50% of that on average cropland, and crop yields are assumed to be unresponsive to commodity price changes. In Scenario 6, cropland allocation is restricted to be determined by historical mixes only to reduce the ease of conversion of land across crops. Across these scenarios we find that changes in fossil fuel prices are very similar to those in the benchmark case; hence these are not included in Table 4.

We also examine the sensitivity of the model results to parameters concerning the transportation fuel sector in scenarios (7)-(9). In scenario (7), the processing cost of BTL is reduced by 45% while leaving the processing cost of lignocellulosic ethanol unchanged. In scenario (8) the demand elasticity of VKT is changed from -0.2 to -0.1 while in scenario (9) the ROW supply elasticity of gasoline is reduced from 0.2 to 0.04.

A change in the upper limit on the land that can be planted under energy crops in a CRD to 10% or 50% leads to a variation in land under bioenergy crops from 3 to 6 million hectares and a variation in land on which crop residues are harvested from 9 to 21 million hectares in 2022. Despite these changes in land under energy crops and crop residues, we find the production of corn ethanol and cellulosic ethanol remains stable as compared to the benchmark scenario. Thus, there are no significant changes in crop prices and overall GHG emissions as compared to the benchmark scenario.

Scenarios (3) and (4) show that high costs of production of energy crops or lower limits on residue collection rates make cellulosic feedstocks more costly, leading to a reduction in cellulosic biofuels and an increase in land under corn and greater reliance on corn ethanol to comply with the RFS mandates as compared to the benchmark scenario. Total land under crop production increases by 1% and 4% relative to the BAU in these two scenarios, respectively; reduced reliance on energy crops lowers expansion of cropland to marginal lands in Scenario (3) while reduced reliance on crop residues increases expansion of cropland for energy crop production on marginal lands in scenario (4). Land under corn increases by 26% and 17% while land under crop residue collection increases by 16% and 3% in scenarios (3) and (4), respectively, relative to the same policy scenario with the benchmark parameters. As a result of increased reliance on first generation biofuels, corn and soybean prices increase significantly (by 26-41% for corn and 21-34% for soybeans). Despite these large effects on land use and crop prices, the impact of high costs of cellulosic biofuels on US GHG emissions reduction is fairly modest, ranging from -1.5% in scenario (3) to -2.1% in scenario (4), only slightly less than -2.2% in the benchmark scenario. The increased reliance on first-generation biofuels in these two scenarios leads to a small positive effect of the RFS on global GHG emissions.

In scenarios (5) and (6), a reduction in crop productivity growth or the ease of land use change across crops reduce the extent to which the intensive margin effects allow corn production to expand and increase the cost of corn as a biofuel feedstock. In both scenarios there is an increased dependence on cellulosic feedstocks to meet the RFS mandates. The two scenarios, however, differ in their impact on crop prices. We find a reduction in crop productivity growth rates lowers corn prices relative to the BAU scenario with the same parameter change because reduced crop productivity growth also raises corn prices in the corresponding BAU scenario and makes corn ethanol less competitive than cellulosic biofuels in the RFS scenario. This leads to reduced demand for corn and lower corn prices in 2022. In contrast, a reduction in the ease of converting land from one crop to another limits the increase in corn acreage under the RFS and raises corn prices. In these two scenarios, land under bioenergy crops and crop residues is 6.6 and 5.5 million hectares, respectively, while the land from which crop residues are harvested increases respectively to 21.1 and 21.5 million hectares. The increase in cellulosic biofuel production under the RFS mandates in turn results in greater GHG emissions reduction in comparison to the benchmark case (-2.4% versus -2.2%) and a reduction in global GHG emissions by 0.2%.

In Table 5, we find that a reduction in the processing cost of BTL (Scenario (7)) significantly changes the mix of biofuels in favor of BTL, leading to a decrease in diesel consumption and price in 2022 by 17% and 27%, respectively. The increase in ethanol consumption, the reduction in gasoline consumption and the reduction in gasoline price due to the RFS are the smallest in this scenario. The domestic and global rebound effects are small in absolute terms, although as a percentage of the small increase in ethanol consumption they appear large. The reduction in GHG emissions is slightly larger than in the benchmark case (2.4% versus 2.2%) because cellulosic biofuels displace diesel which is more carbon intensive than gasoline.

The effects on the fuel sector and on emissions of decreasing the elasticity of VKT demand from -0.2 to -0.1 (scenario (8)) and changing the ROW supply elasticity of gasoline from 0.2 to 0.04 (scenario (9)) are in the same direction as expected. We find that increased consumption of biofuels with a lower demand elasticity of VKT has a larger negative impact on gasoline price (-7.2% versus -6.7% in the benchmark) but it does not lead to much increase in VKT or gasoline consumption; as a result the domestic and global rebound effects on the gasoline market are much smaller (10% and 49% versus 17% and 51% in the benchmark), and the reduction in US and global GHG emissions is larger. On the other hand, a steeper supply curve for gasoline in scenario (9) leads to a large reduction in gasoline price (by 9.4%) and leads to larger domestic and global rebound effects and a smaller reduction in domestic GHG emissions and a small increase in global GHG emissions.

In general, we find that changes in technology and cost parameters and land availability for bioenergy crops that limit the potential to expand production of high yielding energy crops in the agricultural sector affect the mix of biofuels, land uses, and crop prices. The effect of these parameter changes on total land requirement is modest, ranging from 1.1% in the scenario with high costs of production of energy crops to 4.2% in the scenario of low residue collection rates. However, since biofuel production is binding under the RFS alone, changes in cost and technology parameters in the agricultural sector have small effects on liquid fossil fuel prices and generate domestic and global rebound effects not significantly different from the benchmark scenario. Changes in parameters in the fuel sector do affect biofuel mix and fuel prices but do not have a significant impact on land use and crop prices. Across the scenarios considered here we find that the impact of the RFS on domestic GHG emissions ranges from -1.5% in scenario (3) to -2.4% in scenarios (5) and (6). While the inclusion of the average ILUC effect and rebound effect on global gasoline consumption the impact of the RFS on global GHG emissions is rather modest, and ranges from -0.01% to +0.28%. If the ILUC effect is larger, it would further erode the reduction in GHG emissions achieved by the RFS.

V. Conclusions and Discussion

This paper examines the extensive and intensive margin changes in land use in the U.S. likely to be induced by biofuel policies and the implications of these policies for GHG emissions. We explore the implications of the U.S. biofuel policies for both domestic and global GHG emissions as biofuel policies affect global crop and fuel prices, fuel consumption and agricultural production. We also examine the consequent rebound effect on domestic and world gasoline consumption and the ILUC effect on GHG emissions reduction resulting from the production of biofuels in the U.S.

We find that the RFS will lead to a relatively small extensive margin effect of a 3% increase in total land under conventional and bioenergy crop production and about 7% of total cropland will be used for biofuel production in 2022. Much of the impact of the RFS is at the intensive margin: a 9% increase in land under corn coming largely from acreage under other crops, and a modest increase in corn yield growth in response to higher crop prices. The RFS raises corn and soybean prices by 16% and 12%, respectively. Much of the change in acreage at the extensive margin is due to the expansion in energy crop production on current idle/cropland pasture. The sensitivity analysis shows that the extensive margin effects of the RFS can range from 1% to 4% and the impact on corn prices can vary from -2% to 41%.

The RFS would reduce gasoline consumption by 8% and gasoline imports by 10% in 2022. However, each gallon of biofuel reduces 0.83 gallons of energy equivalent gasoline in the U.S. and about half a gallon of energy equivalent gasoline globally. While the RFS reduces GHG emissions from the fuel and agricultural sectors domestically by about 2%, ILUC effects offset this reduction by 0.5- 1%, depending on the size of the ILUC effect assumed. The domestic rebound effect of the policies considered here ranges from 10% to 29% while the global rebound effect lies between 37% and 72%, with the highest global rebound effect obtained in the case where the elasticity of gasoline supply in the ROW is extremely small. The inclusion of emissions due to increased gasoline consumption in the ROW induced by the RFS reduces the net impact of the RFS on global GHG emissions to -0.01% to 0.28% compared to the BAU in 2022.

Volumetric tax credits accompanying the RFS significantly incentivize the production of second generation biofuels and double the acreage under energy crops relative to the RFS alone. Tax credits with the RFS also increase the extensive margin effect and expand cropland by bringing in more marginal land for energy crop production. They reduce the need for land for corn production and keep acreage under other crops such as soybeans at levels similar to those under the BAU scenario, leading to lower corn and soybean prices compared to the BAU scenario in 2022. Gasoline consumption and imports in the U.S. decrease by 13% and 15% respectively, and GHG emissions by the U.S. decrease by about 4% relative to the BAU scenario. This is almost twice the level achieved by the RFS alone. Inclusion of the ILUC effects and the emissions associated with the ROW gasoline consumption offset this reduction considerably and the reduction in global GHG emissions is only about 0.8%.

If the RFS is accompanied by a carbon price policy instead of volumetric tax credits, it would induce a smaller switch from corn ethanol to cellulosic biofuel than the tax credits. However, unlike the volumetric tax credits, the carbon price policy induces greater use of energy crops relative to crop residues. As a result the extensive and intensive margin effects on land use and the crop price effects are somewhat larger than those with the tax credit policy. The carbon price policy combined with the RFS leads to a larger reduction in gasoline consumption and imports than the RFS alone and, more importantly, a negative domestic rebound effect on gasoline consumption because it raises the price of gasoline and diesel compared to the BAU and the RFS alone. The global rebound effect is also smaller in this case. The reduction in domestic and global GHG emissions after including the average ILUC effects and gasoline consumption by the ROW is 5% and 2.5%, respectively.

In summary, the analysis shows that the increase in crop prices under the RFS is likely to be less than 20% in most cases and this increase is much smaller when the RFS is accompanied by volumetric subsidies or a carbon price policy since cellulosic biofuels will substitute for corn ethanol to meet the RFS. The impact of the RFS on GHG emissions reduction in the U.S. is fairly modest in size but greater GHG reduction can be achieved when the RFS is accompanied by volumetric subsidies or a carbon price policy. The ILUC and rebound effects induced by the RFS can erode these GHG emission savings considerably and even lead to a small increase in global GHG emissions over the 2007-2022 period. Combining an RFS with a carbon price policy could offset the rebound effect and enhance the energy security and GHG mitigation achieved by the mandated level of biofuel production under the RFS.

Table 1: Model Validation for 2007

	Observed	Model	Difference (%)
Land Use (M Ha)			
Total Land	123.0	122.8	-0.2
Corn	34.3	32.2	-6.1
Soybeans	28.1	29.7	5.5
Wheat	21.5	21.7	0.7
Sorghum	2.7	2.9	8.2
Commodity Prices ($/MT)			
Corn	142.5	133.2	-6.5
Soybeans	303.7	325.7	7.2
Wheat	197.3	211.3	7.1
Sorghum	145.1	132.0	-9.0
Fuel Sector			
Gas Prices ($/Liter)	0.7	0.7	0.4
Diesel Prices ($/Liter)	0.8	0.8	0.9
Gas Consumption (B Liters)	494.8	495.9	0.2
Diesel Consumption (B Liters)	154.1	154.9	0.5
Ethanol Consumption (B Liters)	26.7	25.2	-5.6
VKT (B Kilometers)	5184.9	5183.1	0.0

Table 2: Effects of Biofuel Policies on the Agricultural Sector in 2022

	BAU 2007	BAU 2022	RFS	RFS with Volumetric Subsidies	RFS with Carbon Tax
Total cropland (M ha)	122.1	121.7	125.7	126.3	126.5
Corn (M ha)	31.8	30.0	32.8	27.0	28.8
Soybeans (M ha)	30.2	30.0	28.2	29.2	28.9
Land for Corn ethanol (M ha)	4.2	3.3	6.8	0.0	2.4
Crop residue collection (M ha)			13.5	38.3	12.2
Energy crops (M ha)			5.1	10.1	9.3
Corn price ($/MT)	145.6	131.4	151.9	118.8	136.3
Soybean price ($/MT)	335.1	329.6	369.9	317.4	326.3

Table 3: Effects of Biofuel Policies on the Fuel Sector and GHGs in 2022

	BAU 2007	BAU 2022	RFS	RFS with Volumetric Subsidies	RFS with Carbon Tax
Gasoline price ($/Liter)	0.73	0.87	0.81	0.78	0.91
Diesel price ($/Liter)	0.77	0.81	0.81	0.81	0.92
First generation biofuels (B Liters)	18.1	18.0	35.9	3.5	15.1
Second generation biofuels (B Liters)			58.4	118.3	79.2
Gasoline Consumption (B Liters)	499.3	495.4	454.6	437.9	441.0
Gasoline Import (B Liters)	335.6	314.1	280.8	267.3	269.6
ROW gasoline consumption (B Liters)	654.2	712.2	728.8	737.1	735.1
Domestic rebound effect (%)			17.4	16.5	-8.5
Global rebound effect (%)			51.1	52.6	37.2
GHGs (B MT) (a)		34.3	33.6	33.0	32.7
Percentage Change in (a) (%)			-2.17	-3.86	-4.60
GHGs with Average ILUC (B MT) (b)		34.4	33.8	33.2	33.0
Percentage Change in (b) (%)			-1.62	-3.35	-4.04
GHGs with High ILUC (B MT)		34.5	34.0	33.4	33.3
US GHG with Average ILUC and ROW Gasoline Emissions (B MT) (c)		67.6	67.5	67.0	66.9
Percentage Change in (c) (%)			-0.05	-0.79	-1.04

Table 4: Sensitivity Analyses for Parametric Assumptions for the Agricultural Sector (%)[1]

Scenarios[2]	Benchmark	(1)	(2)	(3)	(4)	(5)	(6)
Total cropland	3.3	3.3	2.0	1.1	4.2	3.8	3.5
Crop residue collection (M ha)[3]	13.5	9.4	21.3	16.1	2.6	21.1	21.5
Energy crops (M ha)[3]	5.1	5.9	2.9	0.0	5.9	6.6	5.5
Land under corn	9.2	7.9	12.7	25.7	16.5	0.9	5.5
Land under soybeans	-6.0	-5.5	-7.1	-12.5	-8.6	1.1	-3.5
Corn price	15.6	13.6	19.7	40.9	25.7	-2.1	26.7
Soybean price	12.2	10.8	16.1	34.0	20.6	-6.0	5.3
Domestic rebound effect[4]	17.4	17.6	17.3	16.4	16.6	17.5	17.4
Global rebound effect[4]	51.1	51.2	50.9	50.0	50.6	50.6	51.4
US GHG Emissions	-2.2	-2.2	-2.0	-1.5	-2.1	-2.4	-2.4
US GHG with Average ILUC	-1.6	-1.7	-1.5	-1.0	-1.4	-1.9	-1.9
US GHG with High ILUC	-1.1	-1.1	-1.0	-0.4	-0.8	-1.4	-1.4
US GHG with Avg. ILUC and ROW Gasoline Emissions	-0.05	-0.07	-0.01	0.27	0.03	-0.21	-0.18

1. % change is calculated under the RFS relative to the corresponding BAU scenario with the changed parameters.
2. Scenarios: (1) upper limit of 50% on energy crop acres in a CRD; (2) upper limit of 10% on energy crop acres in a CRD; (3) high costs of production of miscanthus and switchgrass; (4) low residue collection rates (5) low rate of yield increases; and (6) historical mixes only.
3. Since there is no cellulosic biofuel production in the BAU, we report absolute numbers under crop residue collection and perennial energy crops.
4. Rebound effects under the mandate scenario are calculated relative to the corresponding BAU scenario with the same parameters.

Table 5: Sensitivity Analyses for Parametric Assumptions for the Fuel Sector (%)[1]

Scenarios[2]	**Benchmark**	**(7)**	**(8)**	**(9)**
Total cropland	3.3	3.5	3.3	3.3
Crop residue collection (M ha)[3]	13.5	14.3	13.3	14.5
Energy crops (M ha)[3]	5.1	5.7	5.1	5.2
Corn price	15.6	16.3	15.4	15.6
Soybean price	12.2	13.2	12.4	10.9
Gasoline price	-6.7	-1.1	-7.2	-9.4
Diesel price	-1.1	-26.9	-1.1	-1.1
Domestic rebound effect[4]	17.4	29.0	10.4	23.1
Global rebound effect[4]	51.1	57.0	49.0	72.5
US GHG Emissions	-2.2	-2.4	-2.5	-1.9
US GHG with average ILUC	-1.6	-1.8	-1.9	-1.4
US GHG with high ILUC	-1.1	-1.3	-1.4	-0.9
US GHG with Avg. ILUC and ROW Gasoline Emissions	-0.05	-0.53	-0.17	0.28

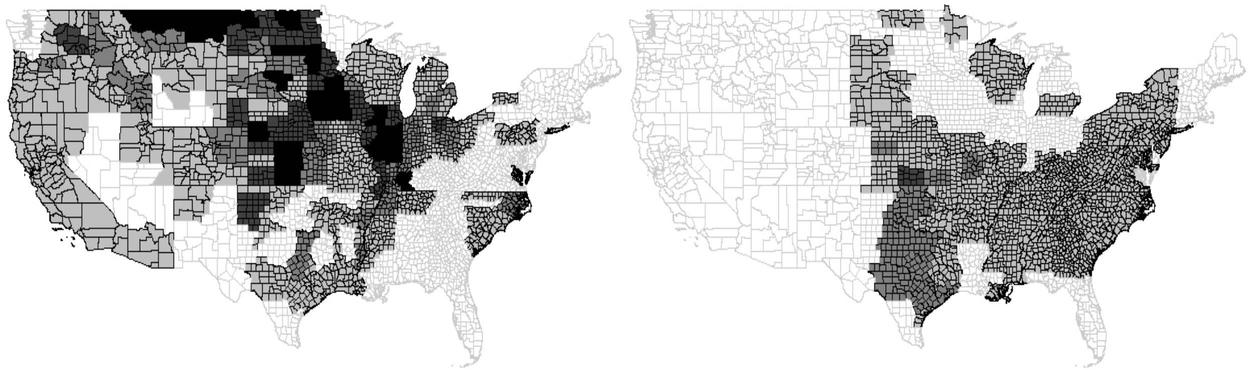
1. Percentage change is calculated under the RFS relative to their corresponding BAU computed with the changes in parameters under each scenario.
2. Scenarios: (7) low processing costs of BTL; (8) low demand elasticity of VKT; and (9) low gasoline supply elasticity.
3. Since there is no cellulosic biofuel production in the BAU, we report absolute numbers under crop residue collection and perennial energy crops.
4. Rebound effects under the mandate scenario are calculated relative to the corresponding BAU scenario with the same parameters.

Figure 1: Spatial Distribution of Crop Residues and Bioenergy Crops

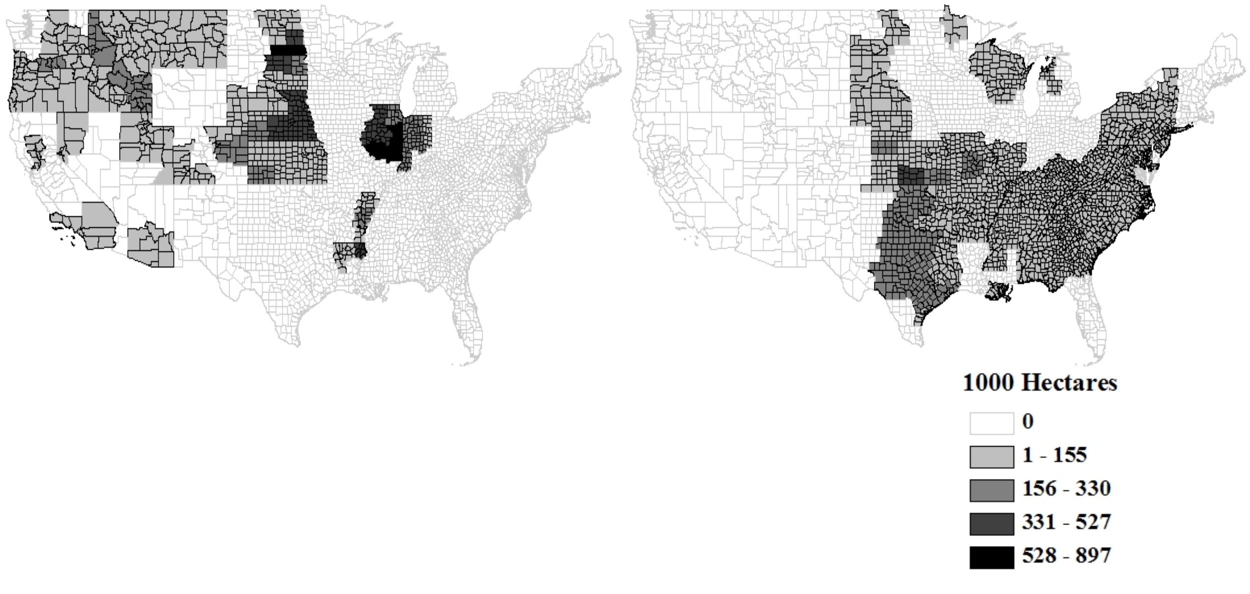
Crop residues Bioenergy crops

(a) Mandate alone

(b) Mandate with volumetric subsidies



(c) Mandate with a carbon tax



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