Meeting the Mandate for Biofuels: Implications for Land Use and Food and Fuel Prices

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Abstract

Biofuels have been promoted to achieve energy security and as a solution to mitigating climate change. This research presents a framework to examine the extent to which biofuel mandates and subsidies reduce gasoline consumption and their implications for the food and fuel prices. A dynamic, multi-market equilibrium model, Biofuel and Environmental Policy Analysis Model (BEPAM), is used to estimate the effects of these policies on cropland usage between food crops and fuel crops and food and fuel prices, and to analyze the incentives provided by alternative policies for the mix of biofuels from corn and various cellulosic feedstocks that are economically viable over the 2007-2022 period. The provision of biofuel subsidies that accompany the mandate under the Renewable Fuel Standard (RFS) is found to significantly change this mix in favor of cellulosic biofuels produced from high yielding grasses and reduce the adverse impact of the RFS alone on food prices.

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Concerns about energy independence, high oil prices and climate change mitigation have led to increasing policy support for the production of biofuels in the U.S. In 2008, the production of U.S. corn ethanol has been more than tripled relative to 2001 with the production of 9 billion gallons using one-third of U.S. corn production (RFA 2010; USDA 2010). Prices of agricultural commodities have doubled between 2001 and 2008, reached the record high levels by the middle of 2008 (USDA/ERS 2010). Although several studies (Abbott et al. 2009; Henderson 2008; Troyer 2008) have concurred that the recent trend in food prices is the combined effect of biofuel production as well as several other factors such as low supply relative to demand, rising oil prices, and the devaluation of the dollar, biofuels have been blamed for the increases in food prices because the period of rapid food price increase coincided with increased biofuel production.

The rapid growth in biofuel production, particular ethanol made from corn, can be expected to increase the prices of agricultural commodities by increasing the demand for corn and shifting cropland from the production of other crops to corn production. Increased corn prices in turn will cause food/feed consumers to shift from corn to other crops so that prices of other crops will increase. The impact of biofuel production on food prices is likely to be mitigated not only by productivity enhancement in food crops, but also by using cellulosic biofuels instead of corn ethanol. Unlike corn ethanol, cellulosic biofuels can be produced from several different feedstocks such as crop residues, perennial grasses (such as miscanthus and switchgrass) and woody biomass. Bioenergy crops can also be productive over a wide geographic range in temperate regions, and potentially more productive in their use of land

(Khanna 2008).

A commercial technology to produce cellulosic biofuels is yet to be developed. To promote their production, the Energy Independence and Security Act (EISA) of 2007 imposes a Renewable Fuels Standard (RFS) that sets annual targets for blending biofuels with gasoline over the 2007-2022 period with a substantial portion of these to be met by cellulosic biofuels. Additionally, the Food, Conservation, Energy Act (FCEA) of 2008 provides a variety of subsidies for the production of cellulosic feedstocks and for blending biofuels with gasoline.

In this paper, we analyze the extent to which the RFS is likely to impose a tradeoff between fuel and food production, and examine the mix of cellulosic feedstocks that are economically viable under alternative policy scenarios and their implications for the use of cropland acreage and for food and fuel prices. We develop a dynamic, multi-market equilibrium model, Biofuel and Environmental Policy Analysis Model (BEPAM), which analyzes the markets for fuel, biofuel, food/feed crops and livestock for the period 2007-2022. We consider biofuels produced not only from corn but also from several cellulosic feedstocks while distinguishing between domestic gasoline supply and gasoline supply from the rest of the world. BEPAM treats each Crop Reporting District (CRD) as a decision making unit where crop yields, costs of crop and livestock production and land availability differ across CRDs. Food and fuel prices are endogenously determined annually and used to update price expectations, cropland acreage and land use choices.

The rest of the paper is organized as follows. In Section II we review the existing literature and the key contributions of our research. In Section III we briefly describe the current legislations whose effects are being analyzed here. Section IV describes the simulation model. Data used for the simulation model is described in Section V followed by the results and conclusions in Sections VI and VII.

II. Previous Literature

A number of studies have examined the implications of biofuel production and policies for food/feed prices and land use. Using the partial equilibrium FAPRI model, Elobeid et al. (2007) analyze the long run effects of crude oil price changes on demand for ethanol and corn while Elobeid and Tokgoz (2008) expand that analysis to show the extent to which the effects of expansion in corn ethanol production on food/feed prices can be mitigated by liberalizing import of biofuels from Brazil. More recently, Fabiosa et al. (2009) use the model to obtain acreage multiplier effects of corn ethanol expansion. These studies (like Tyner et al. 2008) consider an exogenously given price of gasoline and assume that ethanol and gasoline are perfectly substitutable. As a result, the price of ethanol is determined by the price of gasoline (based on its energy content relative to gasoline) and there is a one-directional link between gasoline prices and corn prices, resulting in a perfectly elastic demand for corn at the break-even price at which ethanol refineries can make normal profits. These studies also assume that crop yields are constant over time.

Ferris and Joshi (2009) use AGMOD to examine the implications of the RFS for ethanol and biodiesel production (2008-2017), assuming perfect substitutability between gasoline and ethanol and no cellulosic biofuel production. They find that the mandate could be met by potential crop yield increases and a decline in land under the Conservation Reserve Program and cropland pasture.

Unlike the models used in above studies which focus only on corn ethanol, the POLYSYS model includes various bioenergy crops and investigates land use impacts of biofuel and climate policies (Ugarte et al. 2003). Walsh et al. (2003) apply POLYSYS to examine the potential for producing bioenergy crops at various exogenously set bioenergy prices. English et al. (2008) analyze the effects of the corn ethanol mandate (assuming that cellulosic biofuels are not feasible) and show that it will lead to major increases in corn production in the Corn Belt and in fertilizer use and soil erosion over the period 2007-2016. Most recently, Ugarte et al. (2009) apply POLYSYS to analyze the implications on agricultural income, over the 2010-2025 period, of various carbon prices and carbon offset scenarios under a GHG cap and trade policy assuming the RFS exists.

The impact of climate change policies on the agricultural sector and biofuel production has been examined by McCarl and Schneider (2001) using FASOM, a multi-period, price endogenous spatial market equilibrium model, with a focus on land allocation between agricultural crops and forests. Like the above studies, FASOM also assumes that gasoline and ethanol are perfectly substitutable, but determines the price of gasoline endogenously using an upward sloping supply curve for gasoline. The model includes an autonomous time trend in crop yields and considers various bioenergy feedstocks, such as crop and forest residues, switchgrass, and short-rotation woody crops. McCarl and Schneider (2001) investigate the competitiveness of various carbon mitigation strategies and find that at low carbon prices soil carbon sequestration through a change in cropping practices can be competitive while at high carbon prices abatements can be achieved mainly by use of biomass for power generation and aforestation. They also find that a price of $110 per metric ton of CO_2 would be needed to stimulate production of biofuels. Most recently, Baker et al. (2009) use FASOM to analyze the effects of climate legislation on the agricultural sector while assuming the RFS is implemented (like Ugarte et al. 2009).

In addition to these partial equilibrium studies, the general equilibrium GTAP model has been used to examine the global land use effect of corn ethanol mandate in the U.S. and a biofuel blend mandate in European Union in 2015, assuming no cellulosic biofuel production (Hertel et al. 2010) and imperfect substitutability between gasoline and ethanol (Birur et al. 2008). Reilly et al. (2009) use the general equilibrium EPPA model to examine the implications of greenhouse gas reduction targets over the 2015-2100 period for second generation biomass production and changes in land use. Their simulations suggest that it is possible for significant biofuel production to be integrated with agricultural production in the long run without having dramatic effects on food and crop prices.

The model developed in this paper differs from the existing models in the literature in several aspects. First, we allow imperfect substitutability between gasoline and ethanol. Bottlenecks within the ethanol distribution infrastructure, the existing stock of vehicles and constraints on the rate of turnover in vehicle fleet limit the substitutability between biofuels and gasoline. Empirical evidence shows that biofuel prices are not simply demand driven (based on energy equivalent gasoline prices and perfect substitutability); instead they have been observed to be correlated with their costs of production as well.[1] It is difficult to estimate and predict the substitution possibility between these fuels in the near future as it is directly related to the vehicle fleet structure. Therefore, we examine the implications of a range of substitutability between gasoline and ethanol and implicitly derive the demand for the two fuels. Hayes et al. (2009) show that incorporating imperfect substitutability between ethanol and gasoline in the FAPRI model results in a substantially smaller impact of a change in crude oil prices on demand for ethanol and land use than in Tokgoz et al. (2007). Additionally, we assume two upward sloping supply functions of gasoline and allow biofuel production to have a feedback effect on gasoline prices and thus on the demand for biofuels (as in Hayes et al. 2009). The U.S. accounts for 23% of world petroleum consumption, and about 57% of the consumption is imported from the rest of the world (EIA 2010); thus the change in U.S. oil demand can significantly affect world oil prices. To capture the effect of biofuel policy on gasoline prices, this study considers gasoline supply from domestic producers and the rest of world. The sensitivity of model results to the magnitude of the elasticities of supply of gasoline is also examined.

Crop yield changes over time influence the land needed to meet food and fuel needs to meet biofuel mandates. Dumortier et al. (2009) show that introduction of even a 1% increasing trend in corn yield in the FAPRI model can substantially reduce the corn acreage in response to changes in gasoline and biofuel prices We allow for changes in crop yields over time from two sources, an endogenous price effect and an autonomous technology effect, using econometrically estimated elasticities and time trend (Huang et al. 2010).

Existing models such as FASOM rely on historically observed crop mixes to constrain the outcomes of linear programming models and generate results which are consistent with farmers' planting history. To accommodate new bioenergy crops and unprecedented changes in crop prices in the future FASOM allow crop acreage to deviate 10% from observed historical mixes. Instead of an arbitrary level of flexibility, we use the estimated own and cross price crop elasticities to limit the flexibility of crop acreage changes.

III. Policy Background

The EISA established the RFS in 2007 with the goals of 136 billion liters of biofuel production in 2022. The RFS seeks to provide an assurance of demand for biofuels beyond levels that might otherwise be supported by the market. It specifies four separate categories of renewable fuels, each with a separate volume mandate and together totaling to an amount of 136 billion liters per year by 2022. These categories are renewable fuel, advanced biofuel, biomass-based diesel, and cellulosic biofuel. It also requires that each of these mandated volumes of renewable fuels achieves certain minimum thresholds of GHG emission performance. Of the total requirement for 136 billion liters of renewable fuel in 2022, 80 billion liters should be advanced biofuels (obtained from feedstocks other than corn starch). Of these 80 billion liters, at least 60 billion should be cellulosic biofuels derived from ‘renewable biomass’. Cumulative production of biofuels over the 2007-2022 period mandated by the RFS includes 800 B liters of corn ethanol and 420 B liters of advanced biofuels. Renewable biomass limits the crops and crop residues used to produce renewable fuel to those grown on land cleared or cultivated at any time prior to enactment of EISA in December 2007.

Federal fuel excise-tax credits for corn ethanol have been present for decades. The tax credit peaked at $0.16 per liter in 1984, fell to $0.14 per liter in 1990, and was phased down to $0.13 per liter between 1998 and 2005. The Food, Conservation, and Energy Act (FCEA) of 2008 provides tax credits for blending biofuels with gasoline; the tax credit further decreases to $0.12 cents per liter for corn ethanol till December 2010[2]. The tax credit of $0.27 per liter for cellulosic biofuels is available after December 31, 2008 and before January 1, 2013, and is given to blenders that blend cellulosic biofuels with gasoline. It also requires that cellulosic biofuels should be produced and consumed in the U.S.

IV. The Model

IV.1. General Description

We develop a multi-market, multi-period, price-endogenous, nonlinear mathematical programming model which simulates the U.S. agricultural and fuel sectors and formation of market equilibrium in the commodity markets including trade with the rest of the world. We refer to this model as the Biofuel and Environmental Policy Analysis Model (BEPAM). BEPAM is a dynamic, multi-market equilibrium model, which analyzes the markets for fuel, biofuel, food/feed crops and livestock for an extendable future period (currently set for 2007-2022) in the U.S. The agricultural sector in BEPAM includes several major row crops, livestock and bioenergy crops (crop residues and perennial grasses) and distinguishes between biofuels produced from corn and cellulosic feedstocks. In oil markets, we incorporate sugarcane ethanol imports from Brazil and CBI countries, and gasoline supply not only from domestic production but from the rest of the world. In this paper, we only focus on biofuel mandate and subsidies, and do not consider trade in biofuels. The spatial heterogeneity in yields, costs of production and land availability is also incorporated by assuming each CRD as a decision-making unit. We include cropland and marginal land in the model, and assume that total cropland availability in each CRD can change in response to changes in crop prices. Food and fuel prices are endogenously determined annually and used to update price expectations, cropland acreage and land use choices.

This model determines several endogenous variables simultaneously, including VMT, fuel and biofuel consumption, mix of biofuels and the allocation of land among different food and fuel crops and livestock. This is done by maximizing the sum of 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 (McCarl et al. 1980; Takayama et al. 1971). This model is designed specifically to analyze the implications of biofuel and climate policies on land use patterns, commodity markets, and the environment.

Consumers' behavior is characterized by linear demand functions which are specified for individual commodities, including crop and livestock products, and a linear demand function for miles traveled as a function of fuel prices. In the crop and livestock markets, primary crop and livestock commodities are consumed either domestically or traded with the rest of the world (exported or imported), processed, or directly fed to various animal categories. Export demands and import supplies are incorporated by using linear demand/supply functions. The commodity demand functions and export demand functions for tradable row crops and processed commodities are shifted upward over time at exogenously specified rates.

The crop and livestock sectors are linked to each other through the supply and use of feed items and also through the competition for land (because the grazing land needed by the livestock sector has alternative uses in crop production). The biofuel sector distinguishes biofuels produced from corn and cellulosic feedstock with the two being perfect substitutes in producing miles. The miles demand function and CES production function relating miles generation to fuel uses are calibrated for the base year assuming a specific value for the elasticity of substitution between gasoline and ethanol and observed base year prices and quantities of these fuels and VMT. The demand for VMT is shifted upwards over time and the shares of various fuels are determined endogenously based on the fuel prices. In the case of the biofuels mandate, the model selects the appropriate rule for pricing the blended fuel depending on whether average cost of VMT is greater or smaller than its marginal cost.

BEPAM considers spatial heterogeneity in crop and livestock production activity, where crop production costs, yields and resource endowments are specified differently for each region and each crop assuming linear (Leontief) production functions. The model includes region-specific cropland supply functions to allow cropland expansion through the conversion of marginal lands which are not currently being utilized. The cropland supply response is based on an expected composite crop price index and the lagged total land availability. As the spatial decision unit, the model uses the CRDs in each state by assuming an aggregate representative producer who makes planting decisions to maximize the total net returns under the resource availability and production technologies (yields, costs, crop rotation possibilities, etc.) specified for that CRD. The model covers CRDs in 41 of the contiguous U.S. states in five major regions.[3]

The model uses 'historical' and 'synthetic crop mixes' when modeling farms' planting decisions to avoid extreme specialization in regional land use and crop production. The use of historical crop mixes ensures that the model output is consistent with the historically observed planting behaviors (McCarl and Spreen 1980; Önal et al. 1991). This approach has been used in some existing models also, such as FASOM, to constrain feasible solutions of programming models and generate results which are consistent with farmers' planting history. To accommodate planting new bioenergy crops and unprecedented changes in crop prices in the future FASOM allows crop acreage to deviate 10% from the observed historical mixes. In our model 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 the estimated own and cross price crop acreage elasticities and considering a set of price vectors where crop prices are varied systematically. These elasticities are estimated econometrically using historical, county-specific data on individual crop acreages for the period 1970-2007 as described in Huang and Khanna (2010).

We consider the period 2007-2022 in our analysis. The perennial nature of the energy crops included in the model requires a multi-year consideration when determining producers' land allocation decisions in any given year. For this, we use a rolling horizon approach where for each year of the period 2007-2022 the model determines production decisions and the corresponding dynamic market equilibrium for a planning period of 10 years starting with the year under consideration. After each run, the first year production decisions and the associated market equilibrium are used to update some of the model parameters (such as the composite crop price index, land supplies in each region and crop yields per acre for major crops), based on previously generated endogenous prices, and the model is run again for another 10-year period starting with the subsequent year.

The endogenous variables determined by the model include: (1) commodity 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 year of the 2017-2022 planning horizon and for each region.

IV.2. Algebraic Presentation

We describe the algebraic form of the numerical model using lower case symbols to denote the exogenous parameters and upper case symbols to represent endogenously determined variables. The objective function is the sum of discounted consumers' and producers' surpluses obtained from production, consumption and trade of the crop and livestock products plus the surplus generated in the fuels sector over the 16-year planning horizon 2007-2022 and the terminal values of standing perennial grasses in 2022. The algebraic expression is given explicitly in (1):

$$
\begin{aligned}
&Max: \sum_{0}^{T} e^{-rt} \{ \sum_{z} \int_{0}^{DEM_{t,z}} f^{z}(.)d(.) + \sum_{z} \int_{0}^{EXP_{t,z}} f^{z}(.)d(.) - \sum_{z} \int_{0}^{IMP_{t,z}} f^{z}(.)d(.) + \int_{0}^{MIL_{t}} f^{z}(.)d(.) \\
&- \sum_{r,q} rc_{r,q} ACR_{t,r,q} - \sum_{r,p} pc_{r,p} ACR_{t,r,p} - \sum_{r,q} rs_{r,q} ACR_{t,r,q} - \sum_{r,p} cc_{r} \Delta ACR_{t,r,p} \\
&- \sum_{k} lc_{k} LIV_{t,k} - \sum_{i} sc_{i} PRO_{t,i} \qquad (1) \\
&- \int_{0}^{GAS_{t}} f^{g}(.)d(.) - ec_{c} ETH_{t,c} - ec_{b} ETH_{t,b} \} \\
&+ e^{-rT} \sum_{r,p} (v_{r,p} - w_{r}) ACR_{T,r,p}
\end{aligned}
$$

The first integral term in line of (1) represents the areas under the domestic demand functions from which consumers' surplus is derived. Each integral is associated with a crop, livestock, or processed commodity for which a domestic market demand is considered ($DEM_{t,z}$ denotes the endogenous domestic demand variable in year *t*; $z = \{i, j, k\}$ } denotes the index set for crop commodities (*i*), processed products from crops (*j*), and livestock commodities

(k); $f^z(.)$ denotes the inverse demand function for the commodity involved; and $d(.)$ denotes the integration variable). The next two integral terms account for the areas under the inverse demand functions for exports, $EXP_{t,z}$, and the areas under the import supply functions $IMP_{t,z}$ (such as sugar and sugarcane ethanol). The last integral term represents the area under the inverse demand function for miles traveled (denoted by MIL_t). The demand functions for crop products, livestock products and miles traveled are all characterized by linear demand functions in the current version, but other functional forms, such as constant elasticity demand functions, can be incorporated without difficulty.

The second line in (1) includes the production costs of row crops, perennial crops and crop residues collected for biofuel production, and land conversion costs for marginal lands converted to the production of perennial crops. The land allocated to row crops and perennial crops (acreage) in region r and year t, denoted by $ACR_{t,r,q}$ and $ACR_{t,r,p}$, respectively, may use one of the various production practices which differ by crop rotation, tillage, and irrigation. Fixed input-output coefficients (Leontief production functions) are assumed for both row crops and perennial crops production. The third term represents the cost of collected crop residues (biomass for cellulosic biofuel production) and involves the management options for row crops that produce biomass (specifically, corn stover and wheat straw). The amount of marginal lands converted for perennial grasses are denoted by $\Delta ACR_{t,r,p}$ and cc_r represents the cost per unit of marginal land conversion. The last term denotes the costs of converted marginal lands (such as idle land and crop pasture land) for perennial crops. The land conversion costs include costs for land clearing, wind rowing and any necessary activities for seedbed preparation.

The third line in (1) includes the costs associated with livestock activities. The amount of livestock is represented by $LIV_{t,k}$, and lc_k denotes the cost per unit of livestock category k (again employing Leontief production functions) that is assumed to be the same across all regions. The second term represents the total cost of converting primary crops (corn, soybeans, and sugarcane) to secondary (processed) commodities (oils, soymeal, refined sugar, HFCS and DDGS). The amount of processed primary crop *i* in year *t* is denoted by $PRO_{t,i}$, and sc_i denotes the processing cost per unit of *i*.

The fourth line involves the costs accruing to the fuel sector. The first integral represents the area under the supply functions for gasoline from domestic producers and the rest of the world, whose consumption and price are to be determined endogenously. The next two terms represent the processing costs of corn and cellulosic ethanol in refinery, namely $ETH_{t,c}, ETH_{t,b}$. Finally, the last line reflects the value of the remaining economic life of standing perennial grasses beyond the planning period *T*, denoted by $v_{r,p}$, net of the return from the most profitable cropping alternative in region *r*, denoted by w_r. The latter is used to account for the opportunity costs of land.

In the model, we assume that the consumers obtain utility from vehicle miles traveled (MIL_t), which is produced by blending gasoline (GAS_t), corn ethanol ($ETH_{t,c}$), cellulosic ethanol ($ETH_{t,b}$) and sugarcane ethanol ($IMP_{t,s}$). Gasoline and ethanol are assumed to be imperfect substitutes in miles production while corn ethanol and cellulosic ethanol are perfect substitutes. The total amount of miles generated by use of all sources of fuels is formulated using a constant elasticity production function as shown in equation (2) below:

$$MIL_t = \gamma_t[\alpha_t(ETH_{t,c} + ETH_{t,b} + IMP_{t,s})^{\rho} + (1-\alpha_t)GAS_t^{\rho}]^{1/\rho} \quad \text{for all } t \qquad (2)$$

The regional material balance equations link the production and usage of primary crops, as shown in constraint (3) for primary crop product *i* produced and marketed by region *r*:

$$MKT_{t,r,i} + \{CE_{t,r}\}_{|i=corn} \leq \sum_j y_{r,q,i} ACR_{t,r,q} \quad \text{for all } t,\ r\ ,i \qquad (3)$$

where $MKT_{t,r,i}$ denotes the amount of primary crop product *i* sold in the commodity markets and $y_{r,q,i}$ is the yield of product *i* per unit of the land allocated to crop production activity *q* in region *r*. For corn, $MKT_{t,r,i}$ includes non-ethanol uses and $CE_{t,r}$ is the amount of corn converted to ethanol production (which appears only in the balance constraint for corn).

The amount of primary crop *i* available in the market (excluding the corn used for ethanol) comes from domestic regional supply ($MKT_{t,r,i}$). This total amount is either consumed domestically ($DEM_{t,i}$), exported ($EXP_{t,i}$), processed to secondary commodities ($PRO_{t,i}$), or used for livestock feed ($FED_{t,i}$). This is expressed in constraint (4) below:

$$DEM_{t,i} + PRO_{t,i} + FED_{t,i} + EXP_{t,i} \leq \sum_r MKT_{t,r,i} \quad \text{for all } t, i \qquad (4)$$

Similar to (4), a balance equation is specified for each processed commodity. Like primary commodities, processed commodities can also be consumed domestically, exported, or fed to animals, as shown in constraint (5) below:

$$DEM_{t,j} + FED_{t,j} + EXP_{t,j} \leq \upsilon_{i,j} PRO_{t,i} + \{\sum_r \upsilon_{i,j} CE_{t,r}\}_{j=ddg,i=corn} \quad \text{for all } t, j \qquad (5)$$

where $\upsilon_{i,j}$ denotes the conversion rate of raw product *i* to processed product *j*.

A particularly important component of the model that links the crop and fuel sectors is the conversion of corn and cellulosic biomass to ethanol. During the conversion of corn a secondary commodity, called the Distiller's Dried Grains with Solubles (*DDGS*), is produced as a byproduct. The amount of DDGS produced is proportional to the amount of corn used for ethanol, $CE_{t,r}$, through a fixed conversion rate $\upsilon_{corn,ddg}$, and it can either be fed to livestock as a substitute for soymeal or exported.

The relations between ethanol production and crop production activities are expressed below:

$$E_{t,c} = \alpha \sum_{r} CE_{t,r} \qquad \text{for all } t \tag{6}$$

$$E_{t,b} = \beta\left(\sum_{r,p} by_{r,p} AC_{t,r,p} + \sum_{r,q} ry_{r,q} AC_{t,r,q}\right) \qquad \text{for all } t \tag{7}$$

where α and β denote the amounts of ethanol produced per unit of corn and cellulosic feedstock, respectively, and $by_{r,p}$ and $ry_{r,q}$ are the biomass and crop residue yields in region *r* for respective perennial and crop production activities.

Land is the only primary production factor considered in the model. In each region, the total amount of land used for all agricultural production activities cannot exceed the available land ($al_{t,r}$), which is specified separately for irrigated and non-irrigated land. Due to the steady increase in ethanol consumption the demand for agricultural land is expected to increase through the conversion of some marginal lands (not currently utilized) to cropland. The extent of conversion is assumed to depend on variations in crop prices over time. Therefore, in the model we determine the agricultural land supply 'endogenously'. Specifically, for a given year *t* in the planning horizon 2007-2022, we solve the model assuming a fixed regional land availability for each year of the 10-year production planning period considered in that run. From the resulting multi-year equilibrium solution, we take the first-year values of the endogenous commodity prices and use them to construct a composite commodity price index, CPI. Based on the CPI generated thereby we adjust the land availability for the subsequent run (which considers another 10-year planning period starting with year *t*+1). The land constraint is shown in (8).

$$\sum_{q} ACR_{t,r,q} + \sum_{p} ACR_{t,r,p} \le al_{t,r} \qquad \text{for all } t, r \tag{8}$$

To prevent unrealistic changes and extreme specialization in land use, which may be particularly serious at regional level, we restrict farmers' planting decisions to a convex combination (weighted average) of historically observed acreage patterns ($h_{r,ht,i}$) where subscript *ht* stands for the observed time periods prior to the base year. Historical land uses may be valid when simulating farmer's planting decisions under 'normal' conditions. However, they maybe too restrictive for future land uses given the increased demand for ethanol and unprecedented land use patterns that are likely to occur in the future to produce the required biomass crops. To address this issue we introduce 'hypothetical' acreage patterns ($h'_{r,n,i}$) for each row crop and each region. To generate hypothetical acreage patterns (crop mixes), we first use the historical data on prices and acreages of row crops in each region to estimate acreage elasticities for each row crop with respect to its own price and cross-price changes while controlling other factors, such as social- economic changes and time trend. Then we estimate a number of hypothetical acreages using these price elasticities and considering a systematically varied set of crop prices. The resulting set of actual and hypothetical crop mixes are used in constraint (9) to limit the flexibility in planting decisions, where $\theta_{i,q}$ represents the share of row crop *i* in production activity *q* and $W_{t,r,*}$ represents the weight assigned to historical or hypothetical crop mixes. The latter are defined as variables to be endogenously determined by the model.

$$\sum_{q} \theta_{i,q} ACR_{t,r,q} = \sum_{ht} h_{r,ht,i} W_{t,r,ht} + \sum_{n} h'_{r,n,i} W_{t,r,n} \qquad \text{for all } t, r, i \tag{9}$$

The sum of the endogenous weights assigned to individual mixes must be less than or equal to 1 (convexity requirement), as shown in equation (10).

$$\sum_{\tau} W_{t,r,\tau} + \sum_{n} W_{t,r,n} \le 1 \qquad \text{for all } t, r \tag{10}$$

A similar set of crop mix constraints is introduced for irrigated crops too, which we do not show here, using only the historically observed irrigated land use patterns (no hypothetical mixes for irrigated crops).

Since miscanthus is a non-native grass species, a large scale of miscanthus production may have unforeseen impacts on biodiversity and water quality. To prevent extreme specialization in the production of perennial grasses in some regions, we restrict the land allocated to perennial grasses not to exceed 25% of total land availability in each region ($al_{t,r}$). The constraint is shown in (11).

$$\sum_{p} ACR_{t,r,p} \leq 0.25 * al_{t,r} \quad \text{for all } t, r \tag{11}$$

In the livestock sector, we define production activity variables (number of animals) at national level for each category of livestock except the beef and dairy cattle. Cattle production is given special emphasis in the model for two reasons. First, cattle require grazing land, therefore compete with crop production activities on total land in each region. Second, besides requirements of feed crops directly fed to different types of livestock, DDGS (a byproduct of corn ethanol production) is also used as a feed item that may substitute soymeal (both supplying protein). The regional cattle production activities are aggregated in (12) to obtain the total cattle activity at national level:

$$LIV_{t,cattle} = \sum_{r} CTL_{t,r} \quad \text{for all } t \tag{12}$$

where $CTL_{t,r}$ is the number of cattle stock in region *r* and year *t*. Cattle supply is constrained by the grazing land availability. Therefore, for each region we specify the grazing rates and the supply of grazing land, $GL_{t,r,g}$, where *g* denotes the type of grazing land (namely pasture land, forest land and cropland that can be used for grazing -such as wheat and oats). The amounts of other livestocks (chicken, turkey, lamb, pork and eggs) are also constrained by historical numbers at the national level. Constraint (13) below relates the usage of grazing land and cattle activity in each region:

$$CTL_{t,r} \leq \sum_g GL_{t,r,g} / ga_{r,g} \quad \text{for all } t, r \tag{13}$$

where $ga_{r,g}$ denotes the amount of grazing land required per unit of cattle.

Equations (14) and (15) establish the balances between nutrition needs of livestock activities, in terms of protein and calories, and the amounts of nutrients provided by primary feed crops (grains) and byproducts of crops processing (i.e., soymeal and DDGS):

$$nr_{k,nu} LIV_{t,k} = \sum_i nc_{i,nu} F_{t,i,k} + \sum_j nc_{j,nu} F_{t,j,k} \quad \text{for all t, k} \tag{14}$$

$$FED_{t,z} = \sum_k F_{t,z,k} \quad \text{for all } t,\ k \text{ and } z = i, j \text{ used for feed} \tag{15}$$

where $nc_{z,nu}$ denotes the nutrition content per unit of feed item *z*, and $nr_{k,nu}$ and $F_{t,z,k}$ are the required amount of nutrient *nu* per unit of livestock and the amount of feed item *z* used by livestock category *k*, respectively.

To avoid unrealistic changes in feed mixes, we impose historical feed mixes used by all livestock categories. Constraints (16) and (17) constrain the consumption of feed to be within a convex combination of historical feed uses.

$$FED_{t,z} = \sum_{ht} hf_{z,ht} WF_{t,ht} \tag{16}$$

$$\sum_{ht} WF_{t,ht} \leq 1 \tag{17}$$

Soybean meal and *DDGS* are substitutes in the provision of protein up to a certain share level. Because the share of *DDGS* in total feed consumption of each livestock category is restricted

(Babcock et al, 2008), we impose appropriate upper bounds for DDGS to reflect this aspect of feeding practices.

Livestock commodities can be consumed domestically or exported. The total supply of each livestock commodity is then related to the respective livestock production activity through a fixed yield coefficient, denoted by $ly_{k,s}$. Constraint (18) establishes this relationship:

$$DEM_{t,k} + EXP_{t,k} \leq \sum_{s} ly_{k,s} LIV_{t,s} \quad \text{for all } t,\ k \tag{18}$$

V. Data

The model uses data on costs of producing crops, livestock and biofuels and crop yields. We estimate the rotation, tillage and irrigation specific costs of production in 2007 prices for 15 row crops (corn, soybeans, wheat, rice, sorghum, oats barley, cotton, peanuts, potatoes, sugarbeets, sugarcane, tobacco, rye and corn silage) and three perennial grasses (alfalfa, switchgrass and miscanthus) for each of the 280 CRDs included in our analysis. The primary livestock commodities considered are eggs and milk. The secondary (or processed) crop and livestock commodities consist of oils from corn, soybeans and peanuts, soybean meal, refined sugar, high-fructose corn syrup (HFCS), wool and meat products such as beef, pork, turkey, chicken and lamb. Feedstocks used for biofuel production in the model include corn, corn stover, wheat straw, miscanthus and switchgrass.

Yields: For row crops, we use historical the five year average (2003-2007) yield per hectare for each CRD as the representative yield for that CRD (USDA/NASS 2009). The yields of corn, soybeans and wheat are assumed to grow over time at the trend rate estimated using historical data. These yields are also assumed to be price-elastic with the price elasticities estimated econometrically. The trend rate and elasticities used in the model are based on Huang and Khanna (2010).

We consider two dedicated perennial energy crops, switchgrass (*Panicum viragatum*) and miscanthus (*Miscanthus* × *giganteus*), which have been identified as among the best choices for low-input and high dry matter yield per hectare in the U.S. and Europe (Gunderson et al. 2008; Heaton et al. 2008; Lewandowski et al. 2003). There has been field research on switchgrass in the U.S. since 1991 (McLaughlin et al. 2005). Research on miscanthus in the U.S., on the other hand, was initiated only in 2002 with field trials indicating that miscanthus has relatively high yields in the U.S. Midwest; more than twice those of switchgrass and higher than miscanthus yields observed in Europe (Heaton, Dohleman and Long 2008; Miguez et al. 2008).

In the absence of long term observed yields for switchgrass and miscanthus, we used a crop productivity model MISCANMOD to simulate these yields using GIS data on climate, soil moisture, solar radiation and growing degree days, as described in Jain et al. (2010) The average (2005-2006) delivered yield of miscanthus is 26 metric tons of dry matter per hectare (t dm/ha) while that of switchgrass is 8.5 t dm/ha. Corn stover and wheat straw yields are estimated based on the grain-to-residue ratios and moisture contents in grains reported in Sheehan et al. (2003), Wilcke and Wyatt (2002) and Graham et al. (2007). Average corn stover yield under no-till is 1.5 t dm/ha while for wheat straw it is 0.6 t dm/ha. Ethanol yield from corn grain is 417.3 liters of denatured ethanol per metric ton of corn while cellulosic biofuel yield from an nth-generation stand alone plant is estimated as 330.5 liters per metric ton of dry matter of biomass (Wallace et al. 2005).

Costs of Production: Costs of producing row crops and alfalfa are obtained from the crop budgets complied for each state by state extension services and used to construct the costs of production for each CRD. The costs of labor, building repair and depreciation, and overhead (such as farm insurance and utilities) are excluded from these costs of production since they are likely to be the same for all crops and would not affect the relative profitability of crops. These are, therefore, part of the opportunity costs of using existing land, labor, and capital to produce the bioenergy crops. The costs of producing corn stover and wheat straw include the additional cost of fertilizer that needs to be applied to replace the loss of nutrients and soil organic matter due to removal of the crop residues from the soil. The application rates of N, P, and K per dry metric ton of stover and straw removed are assumed to be constant and are obtained from Sheehan et al. (2003) and Wortmann et al. (2008), respectively. Similar to Malcolm (2008), we assume that 50% of the residue can be removed from fields if no-till or conservation tillage is practiced and 30% can be removed if conventional till is used. In estimating the costs of producing miscanthus and switchgrass, we rely on agronomic assumptions about fertilizer, seed, and pesticide application rates for switchgrass and miscanthus described in Jain et al.(2010). The costs of harvesting biomass (i.e., mowing, raking, baling, staging and storage) are estimated based on the state-specific crop budgets on hay alfalfa harvesting (Jain et al. 2010).

The cost of conversion of corn grain to ethanol is estimated as $0.18/liter in 2007 prices based on Ellinger (2008) and adjusted using the estimates of Wu (2008) while the non-feedstock costs of producing cellulosic ethanol are estimated as $0.39 per liter in 2007 prices (Wallace et al. 2005). We assume that the current unit cost of conversion of feedstock to biofuel, C_{cum}, is a declining function of cumulative production, i.e., $C_{cum} = C_0 Cum^b$, where C_0 is the cost of the first unit of production, Cum is the cumulative production, b is the experience index.[4]

Land Availability: We obtain CRD-specific planted acres for 15 rows crop for the period 1977 to 2007 from USDA/NASS (2009). We use this to construct the cropland available in 2007 and to obtain the historical and synthetic mixes. We also obtain data on land under idle cropland, cropland pasture, pasture and forestland pasture for each CRD from USDA/NASS (2009). The responsiveness of total cropland to crop prices as well as the own and cross-price acreage elasticities for individual crops are obtained from Huang and Khanna (2010).

Crop and Livestock Sector: In the livestock sector we consider demands for several types of meat (chicken, turkey, lamb, beef and pork), dairy and eggs. The demand functions are calibrated using the observed quantities consumed and prices and demand elasticities. The latter are obtained from Adams et al. (2005). The supply of livestock (chicken, turkey, lamb and pork) is constrained by their historical numbers at the national level. 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. The historical livestock data at the national level and production of meat, dairy and eggs for 2003-2007 are used to obtain the average livestock productivity. The state level availabilities of pasture land and forest land in 2007 that can be used for grazing cattle are obtained from ERS/NASS[5]. The data on grazing land requirements for cattle, nutrition requirements (in terms of protein and grain) for each livestock category, and production and processing costs are obtained from Adams et al. (2005). We use the nutrient content of feed crops, soymeal and DDGS to find the least cost feed rations for each type of livestock. The price of DDGS is determined by the lagged prices of corn and soymeal using the relationship estimated by Ellinger (2008). To prevent unrealistic feed mixes consumed by livestock we constrain the consumption of different types of feed based on the historically observed levels obtained from USDA/NASS (2009).

The crops sector consists of markets for primary and processed commodities. The demands for primary commodities, such as, corn and soybeans are determined in part by the demands for processed commodities obtained from them and by other uses (such as seed). The conversion rates from primary crop commodities to processed commodities are obtained from USDA/NASS (2009). The conversion costs are obtained from Adams et al. (2005) and inflated to 2007 prices using the respective GDP deflator. We use two-year (2006-2007) average prices, consumption, exports and imports of crop and livestock commodities to calibrate the domestic demand, export demand and import supply functions for all commodities[6]. We obtain projected amount of crop and livestock commodities for domestic consumption, exports and imports for 2010 and 2020 from FAPRI[7]. Annual growth rates for commodities are calculated by using the one-tenth of total percentage growth rates between 2010 and 2020. This can be written as: annual growth rate= $\frac{1}{10}.\frac{\text{demand in 2020}}{\text{demand in 2010}}$. The demand for miles is assumed to shift out 1% each year after the base year (2007)[8]. The data on prices, consumption, exports and imports are obtained from ERS/USDA while elasticities are obtained from various sources listed in Table 1.

VII. Results

VII.1 Effect of Biofuel and Climate Mitigation Policies on the Agricultural and Fuel Sectors

We first validated the simulation model assuming existing fuel taxes and corn ethanol tax credits and compared the model results on land allocation, crop production, bio-fuel production, and commodity prices with the corresponding observed values in the base year (2007). Since the corn ethanol mandate was exceeded in 2007 it is not imposed as a binding constraint. As shown in Table 2, the differences between model results and the observed land use allocations are typically less than 10% with the exception of sorghum where the deviation in land allocation is 11%. Food prices are generally within 10% of the observed values except for the corn and soybeans prices which are 11% and 12% lower than the actual prices in 2007. The fuel prices and fuel consumption are also simulated well, within 5% deviation from the observed values with the exception for ethanol consumption that is 9%. We consider these results as a fairly good sign of the model's validation capability.

We then examine the effects of two policy scenarios on the agricultural and fuel sectors: biofuel mandates under the RFS alone, and biofuel mandates with volumetric tax credits and compare them to those under a business-as usual (BAU) scenario. The BAU scenario is defined as one without any biofuel policy. In all scenarios considered in the model simulations presented below, we include a fuel tax on gasoline and biofuels, which is set at $0.10 per liter, and assume that the demands for crops and VMT increase over time.

In the benchmark case we assume the following parameter values: price elasticity of miles demand is -0.2 and elasticity of substitution between gasoline and ethanol is 3.95 (Hertel et al. 2008). For the supply of gasoline, we assume two gasoline supply curves to distinguish domestic gasoline supply and gasoline supply from the rest of the world. The short-run supply of domestic gasoline is assumed to be linear with a slope of 0.9 (Greene et al. 2000) while the short-run gasoline supply to the US from the rest of the world is assumed to have a constant elasticity form with a price-elasticity of 2 (National Research Council 2002). To investigate the robustness of the model simulations, we performed a sensitivity analysis using alternative values for various crop production and yield parameters, as discussed in the next section. Results for the benchmark case are presented in Tables 3 and 4.

Business-As-Usual (BAU) Scenario: In the absence of any government intervention in the biofuel market we find that total crop acreage increases by less than 2% from 120.9 to 123.2 M ha with corresponding reductions in pasture land. Corn and soybean acreage would change by 0.7 M ha (2%) and -0.1 M ha (-0.2%) over the 2007-2022 period. Despite the increasing demand for corn, its price decreases by 4% in 2022 due to a 21% increase in corn yield per hectare from 9 metric tons per hectare to 11 metric tons per hectare. In the fuel sector, we find a 9% increase in the price of VMT and 7% increase in gasoline price in 2022 compared to 2007. Corn ethanol production would be about 28 B liters in 2022 or 5% of fuel consumed with no government intervention.

Biofuels Mandate: A binding biofuels mandate would require the production of about 800 B liters of corn ethanol and about 420 B liters of advanced biofuels over the 2007-2022 period. This would increase cumulative production of corn ethanol by 145% relative to the BAU over the 2007-2022 period. The cumulative advanced mandate for cellulosic ethanol is largely met by miscanthus (91%). The mandate leads to a 20% increase in land under corn in 2022 compared to the BAU. This would be met both by a 1% increase in total cropland at the extensive margin and through reductions in land under pasture, soybeans, wheat, rice and barley with a reduction in pasture land being about 6 million hectares. With a high yielding grass like miscanthus, only 6.5 M ha needs to be diverted to miscanthus production and 1.2 M ha to switchgrass production; of 7.7 M ha under bioenergy crops, only 0.4 M ha is converted from cropland and 7.3 M ha from marginal lands. That is because energy crops on marginal lands only involve one-time conversion costs of land, and do not create competition for cropland with row crops. Corn stover and wheat straw would be harvested from 10% and 4% of the land under corn and wheat, respectively. Corn and soybean prices in 2022 are 26% and 23% higher than under the BAU.

The biofuel mandate results in a reduction in gasoline consumption over the period of 2007-2022 by 7% and reduction in gasoline price in 2022 by 8% compared to the BAU level. Gasoline supply from the rest of the world would decrease by 88% in the reduction of total gasoline consumption over the period 2007-2022. As a result of the mandate, the volumetric share of ethanol in total fuel consumption increases to 21% in 2022. The cost of cellulosic biofuels is $0.77 per liter of biofuel, significantly higher than the cost of corn ethanol ($0.69/liter) and gasoline ($0.72/liter) in 2022. However, the displacement of gasoline lowers the overall cost of VMT from $0.087/km to $0.0.086/km and as a result the VMT increases by 0.3% relative to the BAU scenario in 2022. This market-based feedback effect on gasoline prices tempers the extent to which biofuels replace gasoline.

Biofuel Mandate and volumetric tax credits: The provision of tax credits for biofuels leads to two significant shifts in the mix of feedstocks used for biofuels. First, it makes cellulosic ethanol competitive with corn ethanol and reduces cumulative corn ethanol production from its upper limit set under the RFS at 801 B liters to 162 B liters. Cumulative cellulosic ethanol production is 2.5 times of that under a mandate alone from 420 B liters to 1059 B liters over the 2007-2022 period. Second, it increases the share of stover in cumulative cellulosic biofuels from 4% under a mandate alone to 5% under a mandate with subsidies. The corresponding shares of other cellulosic feedstocks slightly fall. The increase in biofuels produced from miscanthus leads to an increase in the land under miscanthus from 6.5 M ha under a mandate alone to 12.4 M ha under a mandate and subsidies. It also increases the acreage from which corn stover and wheat straw are harvested. Figures 1shows the land under bioenergy crops over the 2007-2022 period under the mandate only and under the mandate and tax credit scenarios.

The change in the composition of biofuels due to the subsidy changes the total land under crop production and under various row crops. The need for total cropland diminishes by about 5.5 million hectares relative to the mandate alone since a larger portion of the mandate is met by high yielding feedstocks. Acreage under corn and corn production in 2022 declines by 15% relative to the BAU scenario; corn production in 2022 is, however, still higher than that in 2007 under the BAU due to productivity increase.

The volumetric tax credits result in consumer prices of $0.52 per liter for corn ethanol and $0.50 per liter for cellulosic ethanol that are significantly lower than those under a mandate alone while the gasoline price is marginally higher due to increased demand for fuel relative to the mandate alone. Cumulative VMT over the 2007-2022 period increases by 543B kilometers (0.7%) and gasoline consumption increases by 59.1 B liters (0.7%) relative to the level under the mandate alone. The mandate and subsidies scenario results in the displacement of 547 B liters of gasoline (6%) relative to the BAU scenario over the 2007-2022 period while increasing the cumulative biofuel production by 894 B liters over the 2007-2022 period. With the energy content of ethanol being about 67% of that of gasoline, the kilometers per energy equivalent liter remains at about 9.1 kilometers/liter under the BAU and the mandate and subsidy scenarios over the 2007-2022 period. Thus, much of the increase in total fuel consumption is due to the 0.9% increase in the cumulative VMT (or an additional 0.8 trillion kilometers) under the mandate and subsidies compared to the BAU over this period.

VII.2. Sensitivity Analysis

We examine the sensitivity of our results to changes in some key assumptions about technology and cost parameters in the agricultural sector, and assumptions about land that can be brought into the production of bioenergy crops (see Table 5). Assumptions about cost and technology parameters include the rate of yield increase of row crops, and yields and costs of bioenergy crops. Jain et al.(2010) examine the costs of production of miscanthus and switchgrass under two alternative scenarios, a low cost and a high cost scenarios. The benchmark case considered the low cost of miscanthus and switchgrass production described there. We examine the implications of our assumptions about miscanthus yields, lifetime and costs of production being less optimistic than assumed in the benchmark case. We consider miscanthus lifetime being 10 years instead of 15 years, its yield being 25% lower and its production costs following a high cost scenario (Jain et al. 2010) [9]. We analyze the implications of a 25% higher switchgrass yield which may result from new hybrid varieties currently under development. We also investigate the effects of high production costs for miscanthus and low production costs for switchgrass. In addition, we examine implications of lowering the upper limit that each region can use total available land to grow bioenergy crops from 25% to 10%, and excluding CRP land from being converted into crop production. In each case, only one parameter is changed at a time while all other parameters remain the same. Due to space limitation, we only report the results for the biofuel mandates plus volumetric tax credits scenario.

We present the percentage variations due to the parameter changes relative to the same policy scenarios with the benchmark parameters. We find that the largest impact of a reduction in rate at which crop productivity increases is on land used for corn production, on crop prices, on corn ethanol consumption and price, and on the mix of cellulosic feedstocks. Acreage under corn is about 3% higher than in the benchmark case while corn and soybean prices are 12% higher, than in the benchmark case. Acreages under the harvest of corn stover and wheat straw are about 33% less than in the benchmark case. That in turn increases the acreages under miscanthus and switchgrass by 3% and 14%, respectively. Changes in parameters that make miscanthus more expensive by reducing its lifetime, raising its costs of production or reducing its yields have their largest impact on the mix of biofuels produced from corn, corn stover and straw, miscanthus and switchgrass. They reduce acreage under miscanthus in the biofuel mandate and subsidy scenario by 11% to 96%. Acreages under corn stover and wheat straw would be 108% - 323% and 219% - 1114% higher in these cases than in the benchmark. Acreage under corn would be -0.3% to 33% higher in these cases than in the benchmark while corn prices would be 0.1% to 35% higher. Corn production would need to be increased by 0.1% to 33% to meet the biofuel mandates under the RFS. A 25% increase in switchgrass yields does not make a significant difference to the outcomes except increasing the area under switchgrass by 93%. However, this leads to only a 5% reduction in the area under miscanthus and marginally lowers the crop prices.

Lowering the upper limit of the acreage under bioenergy crops from 25% to 10% reduces the land under miscanthus by 26% because it constrains the expansion of miscanthus acreage in most areas. That in turn increases the acreage under switchagrass by 17% in the areas that have lower production costs of switchgrass and did not fully use their marginal land for the production of switchgrass. Acreages under the harvest of corn stover and wheat straw also increase by 183% and 694% relative to the benchmark. It requires 18% more corn ethanol production than in the benchmark. That leads to increases in corn acreage and price by 3% and 4%, respectively, relative to the benchmark. The exclusion of CRP land significantly decreases the acreages under miscanthus and swithchgrass by 19% and 3%. Acreages under corn stover and wheat straw would be 113% and 353% higher in this case than in the benchmark. The exclusion of CRP land reduce total cropland availability. That in turn reduces the corn acreage and price by 2%. Across the various technology parameter changes considered here, we find that none of them has significant impacts on VMT and gasoline consumption.

VIII. Conclusions and Discussion

Biofuel mandates and subsidy policies have been promoted with the intention of promoting renewable alternatives to reduce dependence on gasoline. Concerns about the competition they pose for land and its implications for food prices have led to a shift in policy incentives towards second generation biofuels from non-food based feedstocks. This paper develops a framework to examine the economic viability of these feedstocks and the extent to which biofuel expansion will imply a trade-off between food and fuel production. It analyzes the differential incentives provided by alternative policies for biofuel production and the mix of biofuels.

Even with the option of high yielding energy crops, we find that a biofuel mandate (without any subsidies) would rely on corn ethanol to the maximum level allowed; miscanthus would meet 91% of the advanced biofuel target, with switchgrass and crop residues meeting the rest. In the benchmark case, the mandate leads to an 20% increase in corn acreage met in part by reducing acreage under soybean and other crops and in part by converting marginal lands to corn. Despite gains in corn productivity over the 2007-2022 period the corn price in 2022 is 26% higher than in the BAU.

The existing volumetric subsidies for cellulosic biofuels make a significant difference to the competitiveness of cellulosic biofuels relative to corn ethanol and shift the mix of biofuels such that 87% of the cumulative biofuels over the 2007-2022 would now be produced from cellulosic feedstocks. This mitigates the competition for land and reduces corn, soybean and wheat prices relative to those with a mandate alone. Corn and soybean prices in 2022 would now be 13% to 8% lower than in the BAU. The reduction in gasoline consumption in the biofuel mandate and subsidy case is about 6% of the BAU levels (over the 2007-2022 period) while the gasoline price in 2022 is 7% lower than the BAU level (Note: A 7% lower gasoline price in 2022 implies a price of $0.73 per liter which is very close to the gasoline price in 2007).

Our analysis also shows the role of productivity enhancing technologies and conversion of marginal lands to cropland both in the traditional crop sector and the bioenergy sector. Yield increases for major crops like, corn and soybeans and the use of high yielding, long-lived energy crops, like miscanthus contribute to mitigating the competition for land and the impact of biofuel production on food prices. Corn price in 2022 would be 10-13% higher if these technologies are less productive or more costly than assumed in the benchmark case. Land conversion from marginal lands such as idle cropland and cropland pasture, to cropland is likely to reduce the adverse impact on crop prices. Corn price in 2022 would be 2-4% higher if these marginal lands are not convertible.

Our analysis abstracted from considerations of risk and uncertainty associated with investment in cellulosic biofuels. Mandates provide assurance of demand for biofuels and induce investment in a technology that is costly and risky. They could also induce learning by doing which in the long run lowers the costs of biofuel production. Thus mandates can enable the development of an infant industry.

Endnotes:

[1] http://www.agmrc.org/renewable_energy/ethanol/the_relationship_of_ethanol_gasoline_and_oil_prices.cfm#
[2] http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_public_laws&docid=f:publ246.pdf
[3] Specifically, we group the USDA Farm Production Regions (see Economic Research Service (ERS), 2009) into the following five major regions: West for Pacific and Mountain, Plains for Northern and Southern Plains, Midwest for Lake States and Corn Belt, South for Delta States and Southeast, and Atlantic for Appalachian and four Northeast states, i.e., Maryland, Pennsylvania, new Jersey and New York.
[4] We assume b for corn ethanol costs is equal to -0.20 (Hettinga et al., 2009) and calibrate C_0 using data on the processing cost and cumulative corn ethanol production in 2007. To calibrate the function for cellulosic ethanol we assume C_{cum} in 2022 is $0.24 per liter (EPA 2009) and use the production quantities specified in the RFS to obtain a value for b of -0.05. These functions imply that the per liter conversion cost for corn ethanol declines by about 30% while that for cellulosic ethanol declines by 41% by 2022.
[5] http:/www.ers.usda.gov/Data/MajorLandUses
[6] An exception is the price of milk which is kept fixed at its observed 2006-2007 level.
[7] http://www.fapri.iastate.edu/outlook/2010/text/Outlook_2010.pdf
[8] We obtain historical data on vehicle miles travelled (VMT) from Federal Highway Administration website: http://www.fhwa.dot.gov/policyinformation/statistics/2008/vm202.cfm, and use average growth rate of VMT from 2000-2008.
[9] This scenario considers higher fertilizer application rates, lower yields in the second year and higher yield losses during harvest.

Table 1: Domestic Demand, Export Demand, Import Supply Elasticities[1]

Commodity	Uses	Shift (%)[2]	Elasticities	Sources
Barley	Domestic	0.0	-0.3	USDA/ERS (2009)
	Export	2.0	-0.2	Adams et al. (2005)
Corn	Domestic	0.8	-0.23	Adams et al. (2005)
	Export	2.0	-0.26	Fortenbery and Park (2008)
Cotton	Domestic	-2.0	-0.18	Adams et al. (2005)
	Export	0.3	-0.65	Bredahl et al. (1979)
Oats	Domestic	-0.4	-0.21	Adams et al. (2005)
Sorghum	Domestic	-1.5	-0.2	Adams et al. (2005)
	Export	2.0	-2.36	Bredahl et al (1979)
Wheat	Domestic	1.0	-0.3	USDA/ERS (2009)
	Export	-2.0	-1.67	Bredahl et al. (1979)
Soybean	Domestic	1.4	-0.29	Piggott and Michael (2002)
	Export	0.4	-0.63	Piggott and Michael (2002)
Soybean Meal	Export	2.0	-1.41	Adams et al. (2005)
Vegetable Oil[3]	Domestic	0.2	-0.18	Piggott and Michael (2002)
	Export	2.0	-2.24	Piggott and Michael (2002)
Rice	Domestic	2.0	-0.11	Gao et al.(1995)
	Export	-0.4	-1.63	Gao et al.(1995)
Peanut	Domestic	0.8	-0.25	Carley and Fletcher (1989)
Beef	Domestic	0.3	-0.75	FAPRI (2009)
	Export	2.0	-0.8	Adams et al. (2005)
Chicken	Domestic	1.4	-0.46	Adams et al. (2005)
	Export	1.4	-0.8	Adams et al. (2005)
Eggs	Domestic	0.8	-0.11	Adams et al. (2005)
	Export			
Pork	Domestic	1.0	-0.83	Adams et al. (2005)
	Export	2.0	-0.8	Adams et al. (2005)
Turkey	Domestic	0.8	-0.53	Adams et al. (2005)
	Export	1.4	-0.8	Adams et al. (2005)
Lamb	Domestic	0.0	-0.4	Adams et al. (2005)
	Import			
Wool	Domestic	0.0	0.4	Adams et al. (2005)
	Export	0.0	-0.8	Adams et al. (2005)
Refined Sugar	Domestic	0.0	-0.368	Adams et al. (2005)
	Import	0.0	0.99	Adams et al. (2005)
HFCS	Domestic	0.5	-0.91	Adams et al. (2005)
	Export	2.0	-0.2	Adams et al. (2005)

Notes:1. This table shows the commodities that can be used for domestic consumption or traded with the rest of the world. Domestic demand for commodities excludes uses for feed and ethanol production, and prices are fixed at 2007 prices if the elasticities are zeros.

2. Demand shifts are computed based on FAPRI 2010 U.S. and World Agricultural Outlook.

3. Vegetable oil includes corn oil, soybean oil and peanut oil.

Table 2: Model Validation for 2007

	Observed	Model	Difference (%)
Land Use (M Ha)			
Total Land	123.05	121.39	-1.35
Corn	34.31	31.30	-8.77
Soybeans	28.15	26.79	-4.81
Wheat	21.52	23.34	8.44
Sorghum	2.69	2.98	11.02
Commodity Prices ($/MT)			
Corn	142.51	127.02	-10.87
Soybeans	303.69	267.04	-12.07
Wheat	197.31	217.05	10.00
Sorghum	145.07	130.57	-10.00
Fuel Sector			
Gas Prices ($/Liter)	0.72	0.72	0.00
Ethanol Prices ($/Liter)	0.61	0.59	-3.11
Gas Consumption (B Liters)	519.94	518.20	-0.34
Ethanol Consumption (B Liters)	23.51	25.60	8.89
Miles Consumption (B Kms)	4863.29	4863.29	0.00

Table 3: Effect of Biofuel and Climate Policies on the Agricultural Sector in 2022

	Baseline 2007	Baseline	Mandate	Mandate with Tax Credits
Land Use (M Ha)				
Total land	120.88	123.18	124.46	118.97
Corn	28.82	29.53	35.38	24.97
Soybeans	27.98	27.93	26.13	28.50
Wheat	24.58	26.14	24.18	25.15
Alfalfa	24.32	23.92	23.65	23.38
Stover			3.45	5.98
Straw			0.97	1.61
Miscanthus			6.49	12.43
Switchgrass			1.15	1.88
Crop Production (Million MT)				
Corn	270.54	330.31	394.71	278.36
Soybeans	77.09	84.52	78.05	89.10
Wheat	59.37	74.15	68.42	71.98
Crop Prices ($/MT)				
Corn	111.53	107.35	135.47	92.99
Soybeans	230.38	243.12	300.24	224.04
Wheat	203.34	197.11	214.42	202.59

Table 4: Effect of Biofuel and Climate Policies on Fuel Sector and Emissions in 2022

	Baseline	Mandate	Mandate with Tax Credits
Prices in 2022 ($/Km or $/Liter)			
Miles	0.087	0.086	0.081
Corn ethanol	0.656	0.685	0.522
Cellulosic ethanol		0.766	0.497
Gasoline	0.785	0.724	0.730
Cumulative Consumption (Over 2007 to 2022) (B Liters or B Kms)			
Miles	82885.78	83110.47	83654.21
Domestic Gasoline	2815.63	2787.28	2745.41
Gasoline from ROW	6110.84	5892.68	5574.73
Ethanol	326.62	1220.99	1220.99
Corn	326.62	801.41	162.19
Stover		16.21	51.14
Straw		1.95	4.10
Miscanthus		381.82	957.53
Switchgrass		19.59	46.03

Table 5: Sensitivity to Technology Parameters[1]

	Rate of yield increase reduced by 50%	Upper limit on energy crop acres reduced from 25% to10%	Lifetime of miscanthus reduced from 15 to 10 years	25% increase in switchgrass yield	High cost of production of energy crops	25% decrease in miscanthus yield	High cost of production of miscanthus	Exclusion of CRP land
Changes in Land Uses (%)								
Total Land	0.87	0.17	0.10	-0.17	3.40	-0.32	1.36	-1.01
Corn	2.92	3.16	-0.29	-0.08	32.71	1.20	25.14	-2.32
Soybeans	0.62	-1.80	0.72	0.04	-6.72	-1.80	-7.03	-2.28
Wheat	0.08	0.96	0.45	-0.06	-1.24	-1.22	-3.32	-4.60
Cellulosic Feedstock Acres (%)								
Stover	-31.69	183.53	107.93	1.02	267.10	162.63	323.46	113.44
Straw	-33.31	694.02	219.24	-0.19	1114.20	549.44	910.21	353.43
Miscanthus	2.62	-26.35	-11.10	-5.13	-61.75	-10.82	-96.25	-18.91
Switchgrass	13.82	16.91	68.85	92.50	-63.32	213.61	717.07	-3.30
Changes in Crop Production and Prices (%)								
Corn Production	-4.48	4.13	0.06	1.41	33.17	2.39	28.23	-0.88
Corn Price	11.97	3.86	0.06	-0.02	34.54	3.90	31.45	1.92
Soybeans Production	-6.04	-3.55	-0.30	1.25	-10.03	-3.14	-9.43	-3.00
Soybeans Price	11.59	2.75	-0.23	-0.38	25.68	2.66	23.43	2.84
Wheat Production	-7.34	-0.30	-0.01	-0.07	-3.10	-1.03	-3.19	-2.90
Wheat Price	7.56	-0.64	0.18	0.46	5.13	0.32	4.35	1.68
Changes in Fuel Prices and Consumption and Mile Consumption (%)								
Gasoline Price	0.00	-0.14	0.00	0.00	-0.27	-0.14	-0.27	-0.08
Corn Ethanol price	3.83	1.15	-0.57	0.38	7.28	1.34	8.43	-0.81
Cellulosic Ethanol Price	-0.40	6.84	2.21	-0.20	12.88	6.04	13.28	4.13
Gasoline Consumption	-0.01	-0.07	-0.06	0.01	-0.18	-0.07	-0.13	-0.08
Corn Ethanol	-1.31	17.56	20.19	-11.26	244.99	10.72	126.07	60.49
Cellulosic Ethanol	0.20	-2.69	-3.09	1.72	-37.53	-1.64	-19.31	-9.27
Mile Consumption	-0.01	-0.07	-0.06	0.01	-0.16	-0.07	-0.12	-0.08

1. Percentage changes are calculated relative to the same policy scenario in the benchmark case.

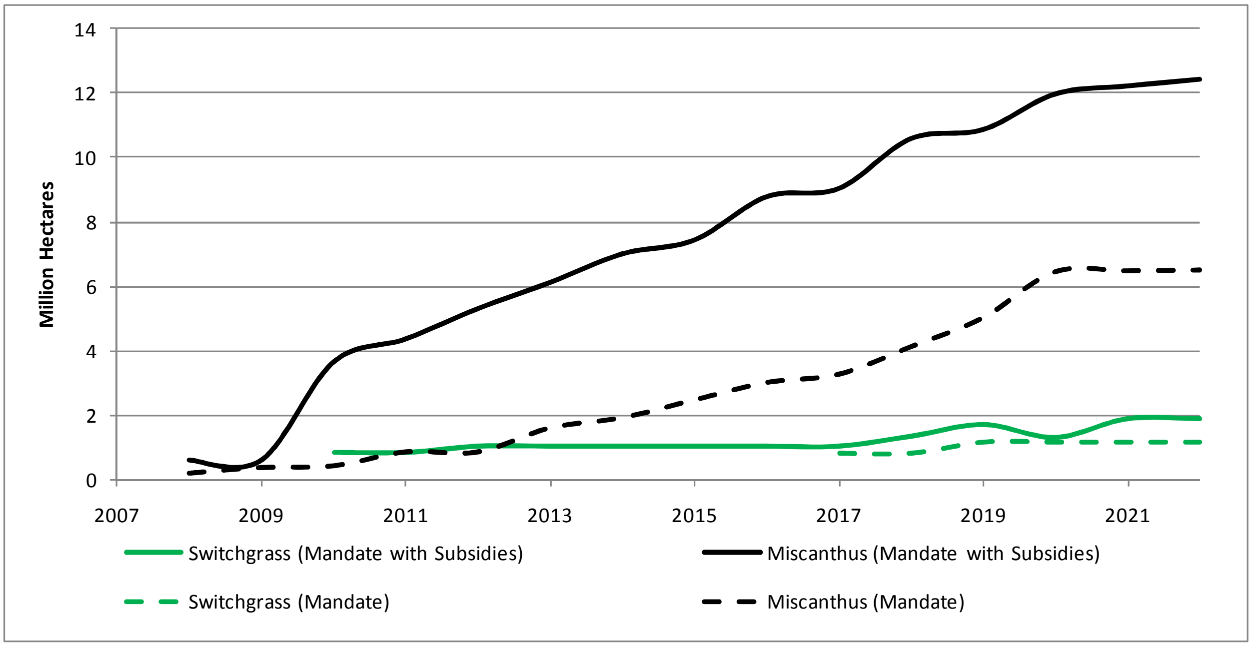

Figure 1: Land Under Energy Crops

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