Meeting the Mandate for Biofuels: Implications for Land Use, Greenhouse Gas Emissions and Social Welfare

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Abstract

Biofuels have been promoted to achieve energy security and as a solution to reducing greenhouse gas (GHG) emissions from the transportation sector. This research presents a framework to examine the extent to which biofuel mandates and subsidies reduce gasoline consumption and GHG emissions 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 welfare costs of these policies relative to a carbon tax 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 RFS alone on food prices. These policies also reduce GHG emissions by 1% relative to a carbon tax of $30 per ton of CO_2e but at a welfare cost of $213 B relative to the tax.

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Concerns about energy independence, high oil prices and greenhouse gas emissions from transportation fuels have led to increasing policy support for biofuels in the form of quantity mandates and tax credits relative to gasoline. Early policy initiatives in the U.S., such as the Energy Policy Act of 2005, sought to promote the production and use of first-generation biofuel produced from corn. Recognition of the potential adverse implications of diverting corn for biofuels for food/feed prices and exports (reviewed in Runge and Senauer 2007) as well as skepticism about the potential of corn ethanol to reduce GHG emissions (Fargione et al. 2008; Searchinger et al. 2008) has heightened energy policy and farm policy support for non-grain based or second-generation, cellulosic biofuels made from feedstocks, such as crop residues, perennial grasses (or dedicated energy crops) and woody biomass.

A commercial technology to produce cellulosic biofuels is yet to be developed. However, these biofuels are potentially more productive in their use of land and have lower GHG intensity per gallon than corn ethanol (Khanna 2008). 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 advanced biofuels, defined by their GHG intensity relative to conventional gasoline. Additionally, the Food, Conservation, Energy Act (FCEA) of 2008 provides a variety of subsidies for the production of cellulosic feedstocks and for blending cellulosic biofuels with gasoline.

While biofuel support policies can be expected to lower GHG intensity of the blended fuel, by displacing gasoline, their effects on gasoline consumption and overall GHG emissions are not certain. Among other things, it will depend on the impact of these policies on the price of the blended fuel which in turn will depend on the costs of producing biofuels, the extent to which gasoline prices respond to lower demand and the substitutability between gasoline and biofuels. A binding mandate accompanied by biofuel subsidies would lower fuel prices and create incentives for increasing fuel consumption, offsetting, at least in part, the benefits of the mandate in lowering GHG intensity. Moreover, biofuel policies can be expected to impact not only fuel consumers by affecting the price of fuel but also food consumers by diverting land from food to fuel production and affecting food\feed production and prices. The impact on food prices depends on the extent to which this effect is mitigated by productivity enhancements in food crop production and shift from the use of food crops towards crop residues and high yielding energy crops for biofuels.

Economic theory suggests that the least cost approach to meeting desired GHG reduction goals is by pricing carbon at its marginal social damage. We analyze the extent to which the RFS is likely to meet its professed goals of reducing GHG emissions and reducing dependence on oil and the welfare costs at which it does so compared to a carbon price policy. We also 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 stylized framework of the food and fuel sectors linked by the limited availability of land to produce food and fuel crops to analyze the mechanisms by which biofuel support prices affect consumer choices and differ from a carbon price policy. We use this to identify some of the parameters likely to influence the impacts of these policies on fuel consumption and GHG emissions. We then operationalize this framework by developing 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. The spatial heterogeneity in yields, costs of production, land availability and GHG emissions is incorporated by assuming each Crop Reporting District (CRD) as a decision making unit. Food and fuel prices are endogenously determined annually and used to update price expectations, cropland acreage and land use choices. Life cycle analysis is used to estimate the GHG intensity of alternative fuels and emissions due to changes in cropping patterns at the CRD level. Our analysis does not include GHG emissions due to indirect land use changes and therefore underestimates the GHG intensity of biofuels. However, it shows that even in this case the effects of biofuels on overall GHG emissions and the costs at which those reductions are realized depends on the government policies that alter transportation fuel use.

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 presents the conceptual framework while Section V describes the simulation model. Data used for the simulation model is described in Section VI followed by the results and conclusions in Sections VII and VIII.

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 and Taheripour 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 an upward sloping supply function 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). We examine the sensitivity of outcomes to the magnitude of this elasticity of supply of gasoline.

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 and Khanna 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.

Unlike, Baker et al. (2009) and Ugarte et al. (2009) who consider the impact of climate policies assuming the RFS is implemented, we consider the implications of biofuel policies for social welfare including both the agricultural sector and the fuel sector and examine the welfare costs of using biofuel policies instead of carbon pricing to mitigate GHG emissions. We quantify the trade-offs between food and fuel prices and between the loss in consumer surplus in the agricultural sector in response to higher food prices and the gain in consumer surplus in the fuel market due to lower fuel prices.

III. Policy Background

We briefly describe the recent legislation that affects biofuels production. Our goal is not to model all the implementation details of these policies, rather we use relevant stylized facts about them to analyze their implications for the agricultural and fuel sectors. 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 and with a lifecycle GHG emission displacement of 50% compared to gasoline). Of these 80 billion liters, at least 60 billion should be cellulosic biofuels derived from ‘renewable biomass’ and achieving a lifecycle GHG emission displacement of 60% compared to gasoline. 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. The life-cycle emissions include GHG emissions at all stages of fuel and feedstock production and distribution and land use changes. 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.

In addition to EISA, the Food, Conservation, and Energy Act (FCEA) of 2008 authorizes the Biomass Crop Assistance Program (BCAP) that provides matching payments up to $45 per dry ton for two years for the amount paid for the collection, harvest, storage and transportation of biomass by a qualified biomass conversion facility.[2] The program also provides a cost-share subsidy of up to 75% of the cost of establishing a perennial energy crop and the opportunity cost of land. Additionally, the FCEA provides tax credits for blending biofuels with gasoline; the tax credit is $0.27 per liter for cellulosic biofuel and $0.12 per liter for corn ethanol.

Climate change legislation is yet to be enacted in the U.S. Bills introduced in 2009 by the Senate (Clean Energy Jobs and American Power Act of 2009 (S. 1733)) and the House (American Clean Energy and Security Act of 2009 (H.R. 2454)) have a number of similarities. Both place caps on the overall amount of GHG emissions allowed from all capped entities and allow capped entities to trade allowances. The capped sectors include transportation and electricity sectors and exclude agriculture. However, agriculture will be affected by the provisions of this bill due to higher energy costs and possibly increased demand for biofuels and by the provision of offset credits for the agricultural sector that may be generated through activities that sequester carbon.[3] Estimates of the market price of allowances over the 2009-2020 period differ across the two bills but are expected to be lower than $30 per ton of CO_2 with the upper bound set by the price at which allowances held in a strategic reserve will be auctioned.

IV. Conceptual Model

We consider an economy with homogenous consumers that demand food (*f*) and transportation (*m*). The latter is measured in vehicle miles traveled (VMT) and produced by blending gasoline (*g*) and biofuels (*e*). Both fuels generate negative externalities, namely the GHG emissions; where GHG emission generated by ethanol is lower than the GHG emission per energy equivalent amount of gasoline. We ignore other negative externalities generated by the use of all fuels for producing miles, such as congestion, air pollution and accidents; and positive externalities associated with biofuels, such as energy security.

We assume that the utility obtained from consumption of transportation and food is separable and given by $U=U_m(m)+U_f(f)$, where $U_m(m)=\int_0^m P_m(m)dm$ and $U_f(f)=\int_0^f P_f(f)df$. The symbols P_m and P_f involved in the integrals represent the demand functions for transportation and food, respectively. The sub-utility functions U_m and U_f are assumed to be strictly increasing and concave, and the demand functions P_m and P_f are downward sloping.

A constant elasticity of substitution function is used to model the production function for VMT using gasoline and ethanol as inputs: $m(g,e)=\gamma[ag^\rho+(1-a)e^\rho]^{1/\rho}$. The elasticity of substitution between gasoline and ethanol is given by $\sigma=1/(1-\rho)$ and ranges between 0 and infinity. We can, therefore, consider gasoline and ethanol as being perfect substitutes, perfect complements or imperfect substitutes in the production of miles.[4]

The GHG emissions generated from a gallon of gasoline and ethanol are assumed to be δ_g and δ_e, respectively, with $\delta_g > \delta_e$. To keep the theoretical model tractable, we only consider a single type of biofuel, and assume food production is a clean technology and does not generate GHG emissions. The aggregate GHG emission, therefore, equals $\delta_g g + \delta_e e$. We denote the value of social damages per unit of GHG emissions by t.

For simplicity, we assume that agricultural land is homogenous in quality and its endowment is given by $\overline{L}$. Let the land dedicated to the production of food and ethanol be L_f and L_e, respectively. Without loss of generality, the outputs of food and ethanol per unit of land can be normalized to one, so $L_f = f$ and $L_e = e$. The agricultural land used to produce food and ethanol should be less than the total land availability, thus, $f + e \leq \overline{L}$. The costs of producing food and fuel are assumed to be strictly convex, denoted by $c(i)$, $i \in \{g, e, f\}$. We assume that marginal cost of producing ethanol is greater than that of gasoline.

IV.1 A Carbon Tax Policy

Standard environmental economic theory shows that a carbon tax set at the marginal social damage from carbon, t, would be the first-best policy to internalize externality costs since it can adjust market prices of fuel to reflect their carbon intensities. The social planner determines the welfare-maximizing choices of miles and food consumption given a carbon price t by solving the following problem:

$$\underset{g,e,f}{Max} \quad U(m) + U(f) - t(\delta_g g + \delta_e e) - c(g) - c(e) - c(f) \tag{1}$$

subject to $m = r[ag^{\rho} + (1-a)e^{\rho}]^{1/\rho}$ and $f + e \leq \overline{L}$.

The miles production function can be substituted into the objective function, which leaves the land use/availability as the only constraint and g, e and f as the only (non-negative) decision variables of the maximization problem. The Lagrangian of the resulting problem is:

$$L = U(m) + U(f) - t(\delta_g g + \delta_e e) - c(g) - c(e) - c(f) + \lambda(\overline{L} - f - e) \tag{2}$$

Assuming that g, e and f are all positive, the first order optimality conditions are:

$$U'(m)m_g - \delta_g t - c'(g) = 0 \tag{3}$$

$$U'(m)m_e - \delta_e t - c'(e) - \lambda = 0 \tag{4}$$

$$U'_f(f) - c'(f) - \lambda = 0 \tag{5}$$

where λ is the Lagrangian multiplier (a measure of the land rent). These equations indicate that the marginal utility of gasoline must equate its social marginal cost which is the sum of the production cost and the marginal external cost of GHG emissions. The marginal benefits of ethanol must equal not only its marginal cost of production and marginal external cost of GHG emissions but also the shadow value of the land diverted from food production to fuel production. Equation (5) implies that at the margin the net returns to land from biofuel production must equal those from food production. In a market economy, consumers will not consider externality costs in their consumption decisions. To induce these optimal outcomes, equations (3) and (4) suggest that taxes should be levied on fuels based on their carbon intensities. Further insight on the implications of a carbon tax for fuel and food consumption and GHG emissions can be gained from the following comparative static analysis using the first order conditions (2)-(4) as shown in Appendix 1.

$$\frac{dg}{dt} < 0 \text{ and } \frac{dm}{dt} < 0 \tag{6}$$

As expected, we find that a carbon tax would unequivocally lower gasoline consumption by raising the gasoline price relative to ethanol, raise the cost of biofuels and the cost of VMT and lower demand for VMT. Its impact on the consumption of biofuels is however ambiguous as shown below.

$$\frac{de}{dt} = \frac{1}{H}\{\frac{s_g}{g}.\frac{1}{\varepsilon_m^d}(\delta_e p_g - \delta_g c'(e)\} - \frac{1}{H}\{\frac{I_m s_g s_e}{g^2 e\sigma}(\frac{\delta_e s_g e}{\sigma EMP_e} + \delta_g g) + \delta_e\frac{p_g}{\varepsilon_g^s g}\} \tag{7}$$

where $H>0$ is the determinant of the matrix derived from total differentiation of the first order conditions (see equation A1.2 in Appendix 1). We define $I_m = P(m).m$ as the expenditure on miles, s_e and s_g are the shares of each fuel's costs in on the expenditure on miles, ε_m^d <0 and ε_g^s >o are own-price elasticities of demand for miles and supply of gasoline, respectively, σ is the elasticity of substitution between ethanol and gasoline, and p_g is the market price of gasoline (equated to its marginal cost *c'(g)*) and expected to be lower than *c'(e)*.[5] We define $EMP_g \equiv -m_{gg}.g/m_g$ >0, $EMP_e \equiv -m_{ee}.e/m_e$ >0, based on Caswell and Zilberman (1986) and refer to them as the elasticity of the marginal productivity of *g* and *e*, respectively.

Equation (7) (obtained from A 1.4 in Appendix 1) shows that the net impact of a carbon price on the consumption of biofuels depends on the magnitudes of the two terms in brackets. The first term in (7) in brackets is always positive and increases in magnitude as the demand for VMT becomes less elastic and as carbon intensity of biofuels $\delta_e < \delta_g$ declines while the gap between *c'(e)* and p_g increases. The second term in (7) is also positive and larger when the ease with which biofuels can be substituted for gasoline increases and the elasticity of supply of gasoline is high. The higher the elasticity of substitution between *g* and *e*, the greater the reduction in demand for gasoline and increase in demand for ethanol when the relative price of gasoline increases. As the elasticity of supply of gasoline increases, a larger part of the carbon price would be passed on to consumers, resulting in greater reduction in demand for gasoline. When the supply of gasoline is infinitely elastic and gasoline and ethanol are perfectly substitutable, $\sigma = \infty$ and if $\varepsilon_g^s = \infty$, the second term in (7) is zero and a small increase in the relative price of gasoline will lead to a large shift towards biofuels. When $\sigma = 0$ and gasoline and ethanol are perfect complements, a carbon tax reduces consumption of both gasoline and ethanol.

The first order conditions can also be used to show that the carbon price umambiguously reduces GHG emissions in two ways: by inducing a reduction in miles and a substitution of ethanol for gasoline (equation (A1.8) in Appendix 1). In the expression below each of the terms is negative and the negative effect on GHG emissions is larger if the elasticity of substitution is high, the supply elasticity of gasoline is high and the elasticity of demand for miles is low.

$$\frac{dGHG}{dt} = \frac{1}{H}\{\delta_g^2[\frac{p_f}{\varepsilon_f^d f} - \frac{c'(f)}{\varepsilon_f^s f} - \frac{I_m s_e}{e^2} EMP_g - \frac{c'(e)}{\varepsilon_e^s e}] - \delta_e^2[\frac{I_m s_g}{g^2} EMP_g + \frac{c'(g)}{\varepsilon_g^s g}] - \frac{2\delta_g \delta_e s_g s_e I_m}{ge\sigma} + \frac{I_m(\delta_g g s_e - \delta_e e s_g)^2}{g^2 e^2 \varepsilon_m^d}\} < 0 \quad (8)$$

Equation (9) shows that the carbon price will raise land rent if it increases biofuel production, since the term within the parentheses is always positive with $\varepsilon_f^d < 0$. The increase in land rent is higher if the own price elasticities of demand and supply of food (ε_f^d and ε_f^s) are small.

$$\frac{df}{dt} = -\frac{de}{dt}, \text{ and } \frac{d\lambda}{dt} = (\frac{c'(f)}{\varepsilon_f^s f} - \frac{p_f}{\varepsilon_f^d f})\frac{de}{dt} \quad (9)$$

IV. 2. Effects of Alternative Policies

Suppose that alternative biofuel policies, such as a mandate to produce/consume a given amount of biofuel and a subsidy on biofuel, are implemented instead of a carbon tax. The quantity mandate and the subsidy rate are fixed exogenously. We use the framework above to examine their impacts on fuel consumption and GHG emissions.

A. Biofuel Consumption Mandate

In contrast to a carbon tax, the consumption mandate requires a fixed amount of ethanol to be produced and consumed: $e = \bar{e}$. The consumption mandate and the land constraint can be substituted into the objective function, which leads to the Lagrangian

$$L = U(m(g,\bar{e})) + U(f) - t(\delta_g g + \delta_e e) - c(g) - c(\bar{e}) - c(f) + \lambda(\bar{L} - f - \bar{e}) \quad (10)$$

In the absence of a carbon price, fuel consumers do not internalize the external costs of fuel while making their fuel choices. Instead the consumption mandate requiring blenders to blend $\bar{e}$ liters of ethanol with gasoline will impose a fixed cost of ethanol on blenders. The average cost of the blended fuel (gasoline and ethanol) will fall as the level of gasoline consumption increases, but the average cost will be greater than marginal cost for low levels of gasoline consumption. If this is the case then blenders can be expected to price fuel based on its average cost in order to avoid negative profits and VMT will be determined by the average cost of a mile rather than its marginal cost. On the other hand, if gasoline consumption is high enough (or if biofuel consumption is small) it could be profitable to use marginal cost pricing of the blended fuel. The following expressions show the latter case. Corresponding expressions for the case where the average cost exceeds the marginal cost of VMT are shown in Appendix 3 and discussed here. First order condition (3) is now as follows, while condition (5) is unchanged:

$$U_m^{'} m_g - c^{'}(g) = 0 \tag{11}$$

Comparative static analysis of optimal solutions with respect to $\bar{e}$ in Appendix 2 shows that

$$\frac{dg}{d\bar{e}} = \frac{-1}{K} \cdot \frac{I_m s_e s_g}{g\bar{e}} \left(\frac{1}{\varepsilon_m^d} + \frac{1}{\sigma}\right) \tag{12}$$

$$\frac{dm}{d\bar{e}} = \frac{-s_e m}{Kg\bar{e}} \left\{\frac{I_m s_g^2 s_e}{g\sigma^2 EMP_e} + \frac{I_m s_g^2}{g\sigma} + \frac{p_g}{\varepsilon_g^s}\right\} \geq 0 \tag{13}$$

where K is the determinant of the matrix under the consumption mandate and always negative as shown in Appendix 2. A consumption mandate raises the cost of biofuels and must have a non-positive impact on the price of gasoline; if ε_g^s is infinity the price of gasoline will be unchanged and it will decrease otherwise as gasoline is displaced.[6] A negative sign of the expression in (12) implies $\left|\varepsilon_m^d\right| < \sigma$. The extent to which the mandate lowers gasoline consumption is higher if the elasticity of substitution is high and the elasticity of demand for miles is low. In the case where blended fuel is sold at its average cost, the impact of the mandate on gasoline consumption is negative if $\left|\varepsilon_m^d\right| < 1$ (see Appendix 3).

The expression in (13) shows that with marginal cost pricing of the blended fuel of VMT, the mandate has a non-negative impact on the demand for VMT. If $\sigma = \infty$ and if $\varepsilon_g^s = \infty$, then $\frac{dm}{d\bar{e}} = 0$. With average cost pricing of the blended fuel, $\frac{dm}{d\bar{e}}$ could be positive or negative as shown in equation A 3.5 in Appendix 3. It is likely to be positive and large if the elasticity of supply of gasoline is inelastic and the elasticity of demand for VMT is high.

Thus a mandate has a negative impact on gasoline consumption like a carbon tax but for different reasons; while the latter raises the price of gasoline the former leaves it unchanged or lower. Moreover, while the carbon tax will unambiguously lower VMT, a mandate may increase VMT. The effect of the consumption mandate on GHG emissions is obtained in A2.5 in Appendix 2 and can be seen to depend (among other terms) on ε_m^d, σ, and ε_g^s.

$$\frac{dGHG}{d\bar{e}} = \frac{1}{Kg\bar{e}}\{I_m s_g[\frac{\bar{e}}{\varepsilon_m^d m \delta_g m_e}(\frac{\delta_e p_g}{\delta_g (c^{'}(e)+\lambda)} - 1) - \frac{\delta_e s_g s_e \bar{e}}{gEMP_e \sigma^2} - \frac{\delta_g s_e}{\sigma}] - \frac{\delta_e p_g \bar{e}}{\varepsilon_g^s} \qquad (14)$$

The first term in the square bracket in (14) is positive since $c'(e) > p_g$ and $\varepsilon_m^d < 0$. The remaining terms are negative. Thus, the overall effect of the mandate on GHG emissions is negative if ε_m^d is small while σ and ε_g^s are large. A high ε_g^s implies that the displacement of gasoline due to the mandate will lead to a smaller reduction in its price and thus a larger reduction in gasoline consumption, particularly if σ is high. A small ε_m^d implies that the impact of the change in fuel price on miles consumption is small; thus, in the event that the mandate reduces the price of the blended fuel, it will not lead to a large increase in miles that could offset the substitution effect of ꞁ□Ê□□□□□ate. Similar conditions are shown in the case that average cost pricing of blended is used in Appendix 3.

Equations (15) and (16) indicate that the biofuel mandate will decrease food production and increase land rent given a limited amount of land resource.

$$\frac{df}{d\bar{e}} < 0 \tag{15}$$

$$\frac{d\lambda}{d\bar{e}} > 0 \tag{16}$$

B. Biofuel Consumption Mandate and Biofuel Subsidy

With a mandate and a subsidy on ethanol we have the following Lagrangian

$$L = U(m(g,\bar{e})) + U(f) - t(\delta_g g + \delta_e e) - c(g) - c(\bar{e}) - s\bar{e} - c(f) + \lambda(\bar{L} - f - \bar{e}) \tag{17}$$

The subsidy on ethanol does not change the first order conditions with a binding mandate. Instead, it lowers the marginal cost of miles by decreasing the marginal cost of ethanol and the marginal cost of miles, which is an increasing function of prices of fuels $P(m) = f(p_e, p_g)$[7].

Moreover, gasoline consumption, $g(m \mid \bar{e}) = \left(\frac{\left(\frac{m}{r}\right)^{\rho} - (1-a)\bar{e}^{\rho}}{a} \right)^{1/\rho}$ with $\frac{dg}{dm} > 0$.

The effect of a biofuel subsidy on gasoline consumption is given by $\frac{dg}{ds} = \frac{dg}{dm}\frac{dm}{dP(m)}\frac{dP(m)}{dp_e}\frac{dp_e}{ds}$ with $\frac{dp_e}{ds} = -1$. After some algebraic manipulations, this can be rewritten as

$$\frac{dg}{ds} = \frac{-g\varepsilon_m^d}{p_e + (\frac{a}{1-a})^{\sigma} p_e^{\sigma} p_g^{1-\sigma}} > 0 \tag{18}$$

We can similarly show that:

$$\frac{df}{ds} = 0 \tag{19}$$

$$\frac{d\lambda}{ds} = 0 \tag{20}$$

$$\frac{dGHG}{ds} = \frac{-\delta_g g\varepsilon_m^d}{p_e + (\frac{a}{1-a})^{\sigma} p_e^{\sigma} p_g^{1-\sigma}} > 0 \tag{21}$$

$$\frac{dm}{ds} = \frac{-ms_g\varepsilon_m^d}{p_e + (\frac{a}{1-a})^{\sigma} p_e^{\sigma} p_g^{1-\sigma}} > 0 \tag{21}$$

With a binding mandate, equations (19) and (20) indicate that a subsidy has no impact on food consumption and land rent since production of biofuels and food does not change. The subsidy results in higher gasoline consumption, VMT and GHG emissions relative to that achieved by the mandate; the effect is larger the greater the elasticity of demand for miles and the greater the elasticity of substitution between gasoline and ethanol.

V. Numerical Model

The conceptual model described above shows the effects of various parameters in the fuel sector on fuel and biofuel consumption decisions and GHG emissions. We expand the simplified representation of the fuel and agricultural sectors above by developing 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. We refer to this model as the Biofuel and Environmental Policy Analysis Model (BEPAM). 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. We also allow the land availability to be responsive to crop prices which in turn allows marginal lands to be used for crop production as crop prices increase, and let crop yields grow over time responding to changes in crop prices.

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 (Takayama and Judge 1971; McCarl and Spreen 1980). 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, which is modeled in a somewhat aggregated fashion in the conceptual framework presented earlier, is expanded to distinguish 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, as discussed above.

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.[8]

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 and McCarl 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). The estimates used are shown in Table A2 in Appendix 5.

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. The model also calculates ex-post some economic welfare measures including producers' and consumers' surpluses, government revenues/costs and net welfare effects, and environmental impact indicators including GHG emissions. For algebraic details of BEPAM, see Appendix 4.

VI. Data

The empirical model uses data on costs of producing crops, livestock and biofuels, crop yields and associated life-cycle GHG emissions. 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). These together with estimates obtained by other studies are shown in Table A2 in Appendix 5.

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 US and Europe (Lewandowski et al. 2003; Gunderson et al. 2008; Heaton et al. 2008). There has been field research on switchgrass in the U.S. since 1991 (McLaughlin and Kszos 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 et al. 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. (2009) 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 per ha while for wheat straw it is 0.6 t dm per ha. Ethanol yield from corn grain is 417.3 liters of denatured ethanol per metric ton of corn while cellulosic biofuel yield from a 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.(2009). 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. 2009).

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.[9]

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 cropland pasture, forestland pasture and rangeland in each state from FASOM. 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). The estimates used are provided in Table A2 in Appendix 5 together with the elasticity estimates of other studies for comparison.

Life-Cycle Greenhouse Gas Emissions: We conduct a life cycle analysis of the above-ground CO_2 equivalent emissions (CO_2e) generated from all the crop and biofuel production activities using the same fertilizer application rates assumed to construct their costs of production. The CO_2e emissions are estimated by aggregating the major GHGs emitted, namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), using their 100-year global warming potential factors. These are 1 for CO_2, 23 for CH_4, and 296 for N_2O. We include the CO_2e generated from various inputs and machinery used in the production of each feedstock, the energy used to produce and transport those inputs to the farm, and the energy used to transport the feedstock to a biorefinery, convert the feedstock to biofuel and transport the biofuel for final consumption net of co-product credits using emissions factors for agricultural inputs, machinery, refinery processes and transportation from the Greenhouse Gases, Regulated Emissions, and

Energy Use in Transportation (GREET) Model (Argonne National Laboratory 2009).

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 FASOM. The supply function specifications for these livestock commodities (other than cattle) are obtained from POLYSYS and involve lagged animal stocks, own and cross price elasticities and price of feed. 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, forest and range lands in 2007 that can be used for grazing cattle are obtained from ERS/NASS[10]. 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 FASOM. 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 FASOM 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[11]. The data on prices, consumption, exports and imports are obtained from ERS/USDA while elasticities are obtained from various sources listed in Table A1 of Appendix 5.

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 1, the differences between model results and the observed land use allocations are typically less than 5% with the exception of wheat and sorghum where the deviations in land allocation are 6% and 7%, respectively. Food prices are generally within 10% of the observed values except for the wheat price which is 13% higher than the actual price in 2007. The fuel prices and fuel consumption are also simulated well, within 5% deviation from the observed values with the exception for ethanol price and consumption that are -12% and 9%, respectively. We consider these results as a fairly good sign of the model's validation capability.

We then examine the effects of four policy scenarios on the agricultural and fuel sectors: a carbon tax set at \$30 per ton of CO_2e, biofuel mandates under the RFS alone, biofuel mandates and various tax credits/BCAP subsidies, and a \$30 per ton of CO_2e tax imposed over and above the existing set of biofuel policies (that is, the RFS and various tax credits/subsidies) and compare them to those under a business-as usual (BAU) scenario. The BAU scenario is defined as one without any biofuel or climate change mitigation policy. In all scenarios considered in the model simulations presented below, we include a fuel tax on gasoline and biofuels, which is set at \$0.38 per gallon, 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, supply elasticity of gasoline is 0.5, and elasticity of substitution between gasoline and ethanol is 2. To investigate the robustness of the model simulations, we performed a sensitivity analysis using alternative values for the above parameters as well as for various crop production and yield parameters, as discussed in the next section. We also considered alternative prices for carbon, but do not report those results for brevity. Results for the benchmark case are presented in Tables 2 and 3.

Business-As-Usual (BAU) Scenario: In the absence of any government intervention in the biofuels market we find that total crop acreage increases by less than 2% from 121.2 to 123.7 M ha with corresponding reductions in pasture land. Corn and soybean acreage would change by 0.8 M ha (2%) and -0.5 M ha (-1.6%) over the 2007-2022 period. Despite the reduction in acreage under corn and increasing demand for corn, its price decreases by 8% over the 2007-2022 period 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 20% increase in the price of VMT and 19% increase in gasoline price in 2022 compared to 2007. Corn ethanol production would be about 40 B liters in 2022 or 7% of fuel consumed with no government intervention.

Carbon Tax: A carbon tax of \$30 per ton of CO_2e induces a switch from gasoline to ethanol with cumulative gasoline consumption falling by 2% while ethanol consumption increases by 4% compared to the BAU scenario over the 2007-2022 period. This tax would increase demand for ethanol by 21.4 B liters over the 2007-2022 period and it raises the corn price by 6% compared with the BAU scenario even though it is accompanied by an increase in the corn acreage and production. The share of corn ethanol in total fuel use would be 7% in

2022; the tax would not be high enough to make cellulosic ethanol competitive with gasoline or corn ethanol. It does, however, raise the cost of gasoline and the cost per VMT, leading to 2% reduction in VMT over the 2007-2022 period. The total GHG emissions from fuels and agricultural production decreases by 0.61 B metric tons (2%) relative to BAU. We also examined the effects of other carbon tax rates and found that a carbon tax of at least $165 per metric ton of CO_2e is needed to induce production of cellulosic biofuels to mitigate GHG emissions.

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 62% relative to the BAU over the 2007-2022 period. The cumulative advanced mandate for cellulosic ethanol is largely met by crop residues (56%) and miscanthus (31%). The mandate leads to a 12% increase in land under corn in 2022 compared to the BAU. This would be met both by a 3% 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 3 million hectares. With a high yielding grass like miscanthus, only 2.3 M ha (2% of total cropland) needs to be diverted to miscanthus production and 0.9 M ha (0.7% of total cropland) to switchgrass production. Corn stover and wheat straw would be harvested from 82% and 70% of the land under corn and wheat, respectively. Corn and soybean prices in 2022 are 12% and 15% higher than under the BAU.

The biofuel mandate results in a reduction in gasoline consumption over the period of 2007-2022 by 4% and reduction in gasoline price in 2022 by 13% compared to the BAU level. As a result of the mandate, the volumetric share of ethanol in total fuel consumption increases to 20% in 2022. The cost of cellulosic biofuels is $0.83 per liter of biofuel, significantly higher than the cost of corn ethanol ($0.59/liter) and gasoline ($0.75/liter) in 2022. However, the displacement of gasoline lowers the overall cost of VMT from $0.154/mile to $0.146/mile and as a result the VMT increases by 1% relative to the BAU scenario in 2022. This market-based feedback effect on gasoline prices tempers the extent to which biofuels replace gasoline. Overall reduction in cumulative GHG emissions is by 0.37 B metric tons (1% relative to BAU) and is less than the reduction achieved by the tax of $30 per ton CO_2e.

Biofuel Mandate and Subsidies: The provision of tax credits for biofuels and BCAP payments 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 802 B liters to 230 B liters. Cumulative cellulosic ethanol production more than doubles from 418 B liters to 991 B liters over the 2007-2022 period. Second, it increases the share of miscanthus in cumulative cellulosic biofuels from 31% under a mandate alone to 54% under a mandate with subsidies. The corresponding share of corn stover falls from 56% to 34%. This is because the volumetric tax credit of $1.01 per gallon of cellulosic biofuel and the BCAP payments encourage the production of high yielding biomass feedstocks that maximize returns to land. The increase in biofuels produced from miscanthus leads to an increase in the share of cropland under miscanthus from 2% under a mandate alone to 7% under a mandate and subsidy. It also decreases the acreage from which corn stover and wheat straw are harvested. Figures 1a and 1b show the land under crop residues and energy crops over the 2007-2022 period under the mandate only and under the mandate and subsidy 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 1 million hectares relative to the mandate alone since a larger portion of the mandate is met by high yielding feed stocks. Acreage under corn and corn production in 2022 declines by 13% 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 various subsidies results in consumer prices of $0.46 per liter for corn ethanol and $0.45 per liter for cellulosic ethanol which 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 245B miles (0.5%) and gasoline consumption increases by 42.3 B liters (0.5%) relative to the level under the mandate alone. The mandate and subsidies scenario results in the displacement of 276 B liters of gasoline (3%) relative to the BAU scenario over the 2007-2022 period. With the energy content of ethanol being about 67% of that of gasoline, the miles per energy equivalent liter remains at about 5.4 miles/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 1.4% increase in the cumulative VMT (or an additional 0.7 trillion miles) under the mandate and subsidies compared to the BAU over this period. The biofuel subsidies result in further decline in GHG emissions relative to the mandate alone and relative to the carbon tax because they induce a switch away from gasoline and corn ethanol towards cellulosic ethanol. The total GHG emissions would now be decreased by about 3% relative to the BAU scenario over the 2007- 2022 period.

Biofuel Support Policies and a Carbon Tax: With the legislation supporting biofuels already being implemented, it is likely that a future cap-and -trade policy will need to co-exist with existing biofuel support policies. In this case we find that there is further increase in the land used for miscanthus production and in cellulosic ethanol production while reducing corn ethanol production. VMT and fuel consumed are higher than those under a carbon tax alone but lower than those under a mandate and subsidy policy. Land under corn and other crops to meet the demand for food and biofuels decreases further relative to the mandate and subsidy scenario. The corn price is 6% lower than in the BAU scenario in 2022 (due in part to lower demand for corn ethanol) while other prices are very similar (Table 2, last column). In comparison with the

BAU scenario, a reduction of 1.5 B metric tons (5%) in GHG emissions is achieved, the highest among the policy scenarios examined.

VII.2 Welfare Effects of Biofuel and Climate Policies

We compare the effects of the various policy scenarios considered above on the cumulative discounted present value of social welfare relative to the BAU scenario over the 2007-2022. Social welfare is measured here by the sum of consumers' and producers' surpluses generated in the agricultural crop and transportation fuel sectors, government expenditures and externality costs (environmental damages) resulting from GHG emissions, over the period 2007-2022. Specifically, in comparison with the BAU scenario, a tax of $30 per ton of CO_2e would increase the total social welfare by $65 B (0.4%) by internalizing the GHG externality. This increase in social welfare is attributed to an increase in government revenue ($639 B), an increase in agricultural producers surplus (8%) and a decrease in externality costs resulting from GHG emissions (2%), when the marginal social damages from GHG are valued at $30 per ton of CO_2e. Under the carbon tax, consumers' surplus from VMT and from agricultural commodities is slightly lower as is the producers' surplus from gasoline production.

The biofuel mandates increase the consumers' surplus from VMT, and agricultural producers' surplus, and decrease the externality costs of GHG emissions. However, these welfare gains cannot compensate for the welfare losses of fuel producers ($340 B) and agricultural consumers ($49 B), leading to a total social welfare loss of $29 B or 0.2% compared with the BAU scenario. Agricultural producers (both row crop producers and bioenergy crop producers) will be better off and their surplus increases by 45%. Given that the gasoline supply function used in this benchmark scenario is fairly inelastic, fuel producers will suffer a loss in surplus of 10%, because the biofuel mandates decrease both the production and the price of gasoline.

Externality costs from GHG emissions would decrease by 1% compared with the BAU scenario due to the decreased carbon emission intensity of the blended fuel.

When the mandate is combined with subsidies, the loss in total social welfare, relative to the BAU, is higher than with a mandate alone and that is because it leads to a larger reduction in the government revenue as compared to a mandate alone. Miles consumers will be the largest beneficiary of the subsidies, with a gain of 3% compared to the BAU. Agricultural consumers are now better off due to lower crop prices relative to the BAU. The surplus for agricultural producers will shrink by 25% compared to the BAU. Their surplus also falls from $428 B with the mandate alone to $370 B with the mandate and subsidies. This reduction in the surplus of agricultural producers is in large part due to the reduced price and production of corn for ethanol production (as the mix of biofuels changes from corn to cellulosics), resulting in lower surplus for continuing crop producers. Provision of subsidies results in a gain of $107 B in surplus for the biomass producers relative to the mandate alone.

In the scenario where biofuel mandates, subsidies and carbon taxes are implemented together, the gains and losses in welfare are very similar to those obtained in the scenario of biofuel mandates plus subsidies. Government revenue will now increase by $322 B compared with BAU because of the collection of the carbon tax. Compared to a carbon tax alone which increases total social welfare relative to the BAU scenario, the combination of biofuel policies and a carbon tax results in a loss in total social welfare of $120 B (0.7%).

In general we find that the overall social welfare effects of biofuel policies with or without a carbon tax are less than 1% of the BAU level. However, effects are large for agricultural crop producers, fuel producers and miles consumers. While the former gain under all policy scenarios, the latter lose 5%-13% of surplus. Miles consumers gain 3% of surplus under a mandate and subsidies scenario but would lose 3% of surplus under a carbon tax.

VII.3. Sensitivity Analysis

We conduct two sets of sensitivity analyses. First we examine the sensitivity of our results on land use, food and fuel prices, GHG emissions and social welfare under the benchmark case to various parameters describing fuel market conditions that are analyzed in the conceptual framework above (see Table 5). Specifically, we analyze the impact of (1) doubling the demand elasticity of VMT, from -0.2 to -0.4, (2) increasing the supply elasticity of gasoline from 0.5 to 0.75, and (3) changing the elasticity of substitution between gasoline and ethanol from 2 (imperfect substitutability) to 10 (perfect substitutability).

Second, we examine the sensitivity of our results to changes in some key assumptions about technology and cost parameters in the agricultural sector (see Table 6). These include assumptions about the rate of yield increase of row crops and yields and costs of bioenergy crops. Jain et al.(2009) 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[12] (Jain et al. 2009). We also analyze the implications of a 25% higher switchgrass yield which may result from new hybrid varieties currently under development. In each case, only one parameter is changed at a time while all other parameters remain the same. Due to space limitation, in Tables 5 and 6, we only report the results for the carbon tax (CT) scenario and the biofuel mandates plus subsidies (MS) scenario.

In Table 5 we present the percentage changes compared to the BAU scenario with the same parameters. The column labeled benchmark shows the percentage change due to CT and

MS relative to the BAU with the benchmark parameters. The effects on the fuel sector and on emissions of doubling the elasticity of miles demand (from -0.2 to -0.4) and of changing increasing the supply elasticity of gasoline from 0.5 to 0.75 are in the same direction as expected from the theoretical model. However, they are not significantly different; suggesting that our results are robust to these assumptions. We find that with a higher elasticity of demand for VMT the CT scenario has a larger negative impact on VMT (-2.7% instead of -1.6%) and leads to a smaller substitution towards corn ethanol (which increases by 1.7% instead of 4.3%). It also leads to a larger reduction in GHG emissions (by 3% instead of 2% in the benchmark case). On the other hand, the MS scenario leads to a larger increase in VMT (by 2%) and a smaller reduction in GHG emissions than in the benchmark case (by 2% instead of 3%).

With a flatter supply curve for gasoline, the CT reduces gasoline consumption by 2.2% instead of 1.8% and increases ethanol consumption by 6.3% instead of 4.3%. The MS scenario now results in a smaller decline in gasoline price and a larger reduction in gasoline consumption and in GHG emissions (3.5% instead of 3.1%). When the elasticity of substitution between gasoline and ethanol is increased from 2 to 10, the CT would lead to a much greater increase in corn ethanol consumption (by 8.7% instead of 4.3%) and therefore larger increases in corn acreage and corn prices than in the benchmark case. In this case, the CT and MS scenarios also result in a larger reduction in gasoline prices, gasoline consumption and GHG emissions (6.0% instead of 3% under the MS in the benchmark case).

In Table 6 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 and on corn ethanol consumption and price. Under the CT and MS scenarios (Table 6, columns A, B), acreage under corn is about 7%-8% higher than in the benchmark case while corn and soybean prices are 11%-17% higher and 12%-21% higher respectively, than in the benchmark case. 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 vs. miscanthus. They reduce acreage under miscanthus in the MS scenario by 8% to 37% (Table 6 columns C, E, F). Acreage under corn would be 11% to 19% higher in these cases while corn prices would be 7% to 13% higher. Corn production would need to be increased by 11% to 19% 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 43% (Table 6, column D). However, this leads to only a 3% reduction in the area under miscanthus and marginally lowers the crop prices. Across the various technology parameter changes considered here, we find that none of them has significant impact on VMT, gasoline consumption or GHG emissions.

VIII. Conclusions and Discussion

Biofuel mandates and subsidy policies have been promoted with the intention of promoting renewable alternatives to reduce dependence on gasoline and to reduce GHG emissions. 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, the mix of biofuels and their effects on GHG emissions and social welfare.

We find that a tax of $30 per ton of CO_2e results in modest changes in land use allocation among crops and in corn ethanol production and would not create incentives for production of cellulosic ethanol. The carbon tax would induce additional production of corn ethanol ranging from 4% to 9% and increase corn prices by 5% to 10% depending on the parameters describing the fuel sector. The tax would reduce GHG emissions by 2% -3% compared to the BAU scenario. The present value of the welfare gains with the carbon tax is $65 B in the benchmark case and ranges between $33 and $73 B across the various parameter assumptions considered here. The upper end of these ranges would be achieved with a high elasticity of substitution between gasoline and ethanol.

Even with the option of high yielding energy crops, a biofuel mandate (without any subsidies) would rely on corn ethanol to the maximum level allowed; crop residues would meet two thirds of the advanced biofuel target, with miscanthus meeting the rest. In the benchmark case, the mandate leads to an 11% increase in corn acreage met in part by reducing acreage under soybean and other crops and in part by converting pasture land to corn. Despite gains in corn productivity over the 2007-2022 period the corn price in 2022 is 12% higher than in the BAU.

The existing volumetric subsidies for cellulosic biofuels and for biomass production make a significant difference to the competitiveness of cellulosic biofuels relative to corn ethanol and shift the mix of biofuels such that two thirds 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 price in 2022 would now be 5% to 13% lower than in the BAU while the GHG emissions reduction ranges from 3% to 6% depending on the fuel market parameters. Unlike the conceptual analysis we find that the mandate and subsidies reduces GHG emissions by more than the mandate alone. This is because it changes the mix of biofuels in favor of the low carbon intensity cellulosic biofuels; as a result the reduction in GHG intensity of fuels is large enough to more than offset the increase in GHG emissions due to the additional VMT induced by the biofuel subsidy. The mandate and subsidies benefits fuel consumers and producers of biomass crops but this is at the expense of crop producers and gasoline producers. The reduction in gasoline consumption in the MS case ranges between 3% to 6% of the BAU levels (over the 2007-2022 period) while the gasoline price in 2022 could be 8% to 17% lower than the BAU level, depending on fuel market parameters (Note: A 17% 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 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 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. While a carbon price generates a net benefit for the fuel and agricultural sectors, the other policies impose a welfare cost ranging from 1% to 1.5% relative to the BAU level. The welfare cost of the mandate and subsidies is $213 B in the benchmark case and ranges between $193 and $218 B across the various parameter assumptions considered here.

Our analysis abstracted from considerations of risk and uncertainty associated with investment in cellulosic biofuels. On the basis of cost-effectiveness a carbon price would be the preferred policy. However, a very high carbon tax would be needed to transition to a low carbon economy given the costs of 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. With a mature technology however, they should be phased out and replaced by performance-based policies, such as a carbon tax or equivalent cap-and- trade policy that is targeted to achieve specific policy goals.

Endnotes:

[1] http://www.agmrc.org/renewable_energy/ethanol/the_relationship_of_ethanol_gasoline_and_oil_prices.cfm#
[2] http://www.fsa.usda.ov/Internet/FSA_File/2008fbbcapsummary.pdf
[3] Both bills also establish offsets credits for the agricultural sector that may be generated through activities that sequester carbon. Due to lack of data at the CRD level on the amount of carbon sequestered in the soil by various agricultural activities we do not consider the incentive effects of payments for offsets in our model. We also do not consider the GHG emissions generated by indirect land use changes(Searchinger, Heimlich et al. 2008).
[4] Those two fuels have previously been modeled both as perfect complements (Vedenov and Wetzstein 2008) and as perfect substitutes (de Gorter and Just forthcoming). The extent of substitutability depends on the stock of flexible fuel motor vehicles. Currently, ethanol is perfectly substitutable with gasoline, in the production of miles, on an energy equivalent basis up to 10% blends. As the stock of flexible fuel vehicles increases, the substitutability between gasoline and ethanol is expected to increase.
[5] By solving cost minimization of miles production, the marginal cost (or price of miles *P(m)*) of miles is expressed as $P(m) = \frac{1}{\gamma}(a^{\sigma} p_g^{\,1-\sigma} + (1-a)^{\sigma} p_e^{\,1-\sigma})^{1/1-\sigma}$
[6] A positive impact on the price of gasoline is only possible if the mandate increases demand for gasoline. In this case the cost per mile would increase since both gasoline and ethanol are then more expensive and VMT must fall. This is inconsistent with increased consumption of both fuels. The expression in (13) must, therefore, be negative

[8] 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.
[9] 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 $0.89 per gallon (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.
[10] http:/www.ers.usda.gov/Data/MajorLandUses
[11] An exception is the price of milk which is kept fixed at its observed 2006-2007 level.
[12] This scenario considers higher fertilizer application rates, lower yields in the second year and higher yield losses during harvest.

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Table 1: Model Validation for 2007

	Observed	Model	Difference (%)
Land Use (M Ha)			
Total Land	122.61	121.44	-0.01
Corn	34.31	32.51	-0.05
Soybeans	28.14	26.80	-0.05
Wheat	21.52	22.85	0.06
Sorghum	2.69	2.87	0.07
Commodity Prices ($/MT)			
Corn	142.51	136.32	-0.04
Soybeans	303.69	282.74	-0.07
Wheat	197.31	223.62	0.13
Sorghum	145.07	137.82	-0.05
Fuel Sector			
Gas Prices ($/Liter)	0.71	0.71	0.00
Ethanol Prices ($/Liter)	0.61	0.54	-0.12
Gas Consumption (B Liters)	519.88	515.93	-0.01
Ethanol Consumption (B Liters)	26.20	28.51	0.09
Miles Consumption (B Miles)	3021.91	3021.91	0.00

Table 2: Effect of Biofuel and Climate Policies on the Agricultural Sector in 2022

	Baseline 2007	Baseline	Carbon Tax	Mandate	Mandate with Subsidi	Mandate with Subsidies and Carbon Tax
Land Use (M Ha)						
Total land	121.24	123.65	123.01	127.64	126.78	126.02
Pasture	296.22	293.24	293.51	290.37	290.80	291.02
Corn	31.00	31.75	32.28	35.45	27.59	26.96
Soybeans	27.45	27.00	27.07	26.35	26.92	26.71
Wheat	23.78	25.68	25.17	24.29	24.98	24.81
Alfalfa	24.01	23.87	23.77	23.66	23.14	23.08
Stover				28.98	24.52	24.18
Straw				17.01	20.28	21.26
Miscanthus				2.34	8.79	9.35
Switchgrass				0.90	0.52	0.50
Crop Production (Million MT)						
Corn	289.03	356.83	361.28	392.85	311.94	302.61
Soybeans	75.52	83.38	84.17	78.11	82.43	81.96
Wheat	57.07	72.62	71.12	69.66	72.42	71.89
Crop Prices ($/MT)						
Corn	123.92	114.63	121.05	128.72	108.29	107.93
Soybeans	251.33	255.13	242.11	294.06	262.55	256.92
Wheat	210.47	198.30	205.59	211.55	200.86	201.76

Table 3: Effect of Biofuel and Climate Policies on Fuel Sector and Emissions in 2022

	Baseline	Carbon Tax	Mandate	Mandate with Subsidies	Mandate with Subsidies and Carbon tax
Prices in 2022 ($/Mile or $/Liter)					
Miles	0.155	0.162	0.146	0.138	0.149
Corn ethanol	0.57	0.61	0.59	0.46	0.48
Cellulosic ethanol			0.83	0.45	0.48
Gasoline	0.86	0.93	0.75	0.77	0.84
Cumulative Consumption (Over 2007 to 2022) (B Liters or B Miles)					
Miles	51068.21	50264.71	51521.88	51767.19	50900.95
Gasoline	8711.41	8552.80	8393.01	8435.31	8284.50
Ethanol	494.74	516.10	1220.98	1220.98	1221.43
Corn	494.74	516.10	802.51	229.33	204.79
Stover			235.32	336.76	341.05
Straw			37.59	105.95	101.73
Miscanthus			129.36	531.76	559.94
Switchgrass			16.21	17.18	13.91
Cumulative Greenhouse Gas Emissions (Over 2007 to 2022) (B MT)					
Emissions	28.88	28.27	28.51	27.99	27.34

Table 4: Effect of Biofuel and Climate Policies on Social Welfare in 2022 ($B)

	Carbon Tax	Mandate	Mandate with Subsidies	Mandate with Subsidies and Carbon tax
Miles Consumers	-411.80	220.90	336.80	-111.19
	-3.2%	*1.7%*	*2.6%*	*-0.9%*
Gasoline Producers	-186.05	-340.46	-297.92	-464.93
	-5.4%	*-9.9%*	*-8.6%*	*-13.5%*
Agricultural Consumers	-14.71	-48.86	12.13	3.63
	-0.7%	*-2.3%*	*0.5%*	*0.2%*
Agricultural Crop Producers	24.75	132.17	74.50	97.19
	8.4%	*44.7%*	*25.2%*	*32.9%*
Government Revenue	638.95	0.00	-291.86	322.10
Externality Cost	13.73	7.38	18.07	32.81
	-2.1%	*-1.1%*	*-2.8%*	*-5.0%*
Total Welfare	64.87	-28.88	-148.27	-120.39
	0.4%	*-0.2%*	*-0.8%*	*-0.7%*

Percentage change in italics is relative to the BAU level

Table 5: Sensitivity to Fuel Sector Parameters[1]

	Benchmark		$\varepsilon_m^d = -0.4$		$\varepsilon_g^s = 0.75$		$\sigma = 10$	
	CT[2]	MS	CT	MS	CT	MS	CT	MS
Changes in Land Uses (%)								
Total Land	-0.52	2.53	-0.59	2.60	-0.40	2.67	-0.28	1.24
Corn	1.68	-13.11	-0.93	-13.71	0.30	-13.22	1.04	-15.59
Soybeans	0.26	-0.31	0.27	-1.07	0.17	-0.95	-0.78	0.68
Wheat	-2.01	-2.73	-1.19	-1.77	-1.19	-1.97	-0.72	-2.92
Cellulosic Feedstock Acres (M Ha)								
Stover		24.52		24.55		24.52		29.65
Straw		20.28		20.28		20.28		20.41
Miscanthus		8.79		8.77		8.79		8.58
Switchgrass		0.52		0.52		0.52		0.44
Changes in Crop Production and Prices (%)								
Corn Production	1.25	-12.58	0.38	-11.32	0.69	-11.59	0.05	-14.07
Corn Price	5.60	-5.53	4.01	-5.37	6.18	-5.12	10.27	-13.62
Soybeans Production	0.95	-1.14	0.79	-0.59	0.28	-0.86	-0.84	1.84
Soybeans Price	-5.10	2.91	-0.98	1.96	-5.10	2.91	4.09	-3.92
Wheat Production	-2.06	-0.27	0.36	1.51	-1.09	0.58	-0.34	-0.62
Wheat Price	3.67	1.29	-2.18	-3.54	0.04	-2.27	-0.80	1.53
Changes in Fuel Prices and Consumption and Mile Consumption (%)								
Gasoline Price	8.31	-10.65	7.08	-9.05	8.55	-8.29	7.17	-17.10
Corn Ethanol price	5.42	-20.55	4.82	-20.53	5.42	-20.48	7.24	-24.25
Cellulosic Ethanol Price ($/Liter)	0.00	0.45	0.00	0.45	0.00	0.45	0.00	0.46
Gasoline Consumption	-1.82	-3.17	-2.84	-2.58	-2.15	-3.70	-2.18	-6.31
Corn Ethanol Consumption	4.32	-53.65	1.67	-51.30	6.34	-51.78	8.74	-29.62
Cellulosic Ethanol (B Liters)	0.00	991.66	0.00	991.43	0.00	991.67	0.00	1247.16
Mile Consumption	-1.57	1.37	-2.66	2.16	-1.82	0.99	-1.50	2.49
Changes in Social Welfare and GHG Emissions (%)								
GHGs	-2.09	-3.07	-3.09	-2.34	-2.36	-3.50	-2.26	-5.97
Social Welfare	0.35	-0.81	0.28	-1.43	0.26	-0.93	0.40	-0.65

1. % change is calculated relative to baseline (BAU) results where baselines change with different parameters;
2. CT denotes carbon tax policy, and MS represents the policy of consumption mandates plus subsidies.

Table 6: Sensitivity to Technology Parameters[1]

	Rate of yield increase reduced by 50%		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
	CT	MS	MS	MS	MS	MS
	A	B	C	D	E	F
Changes in Land Uses (%)						
Total Land	2.58	2.02	2.10	0.04	0.15	0.52
Corn	6.52	8.36	10.76	0.40	18.81	15.07
Soybeans	1.54	0.47	-0.40	-0.21	-2.93	-1.82
Wheat	1.84	-0.17	-0.48	-0.03	-2.30	-1.22
Cellulosic Feedstock Acres (M Ha)						
Stover		9.39	1.22	-0.89	21.00	16.59
Straw		4.18	-19.94	-0.12	0.84	2.42
Miscanthus		4.24	-7.57	-3.18	-37.73	-30.43
Switchgrass		1.60	27.20	43.50	0.40	19.62
Changes in Crop Production and Prices (%)						
Corn Production	-4.40	-2.18	11.85	1.04	18.57	16.08
Corn Price	17.36	10.67	6.90	0.00	13.31	6.87
Soybeans Production	-6.71	-5.98	-0.47	-0.21	-4.30	-2.89
Soybeans Price	21.24	12.41	-1.77	-2.44	9.57	7.55
Wheat Production	-6.55	-8.95	-0.80	-1.24	-4.39	-2.67
Wheat Price	7.10	11.07	2.95	3.13	6.51	3.10
Changes in Fuel Prices and Consumption and Mile Consumption (%)						
Gasoline Price	0.62	-0.25	-0.04	0.00	-0.16	-0.10
Corn Ethanol price	5.95	3.92	2.81	0.04	3.14	0.94
Cellulosic Ethanol ($/Liter)		6.80	0.35	0.26	4.21	3.24
Gasoline Consumption	0.17	-0.03	-0.02	0.00	-0.05	-0.03
Corn Ethanol Consumption	-5.42	-2.83	20.12	-1.14	74.33	54.73
Cellulosic Ethanol (B Liters)		0.65	-4.65	0.26	-17.19	-12.66
Mile Consumption	-0.06	-0.03	-0.02	0.00	-0.04	-0.03
Changes in Social Welfare and GHG Emissions (%)						
GHGs	0.05	-0.11	0.19	0.02	0.70	0.49
Social Welfare	0.09	0.06	-0.02	-0.01	0.07	0.06

[1]Percentage changes are calculated relative to the same policy scenario with the benchmark parameters

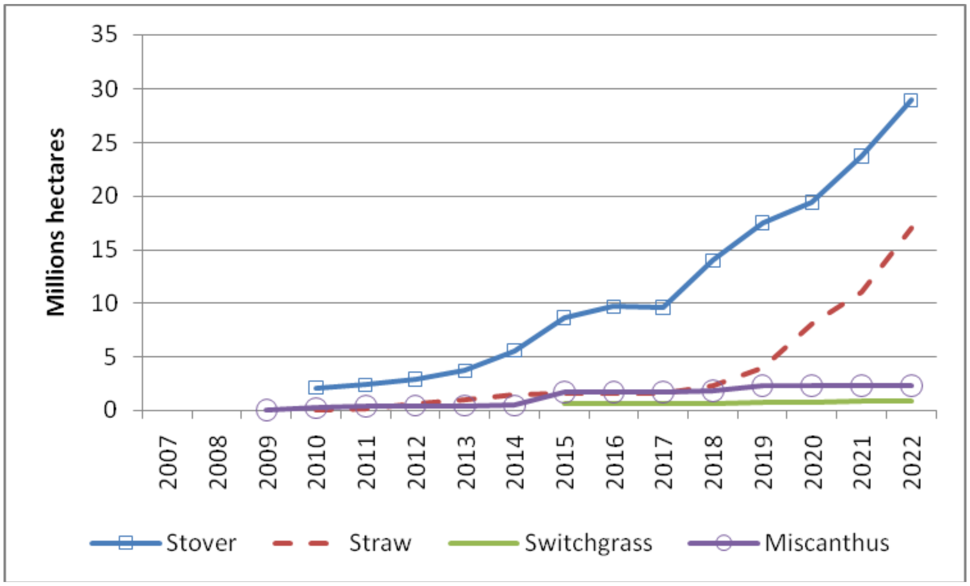

Figure 1a: Land Under Cellulosic Feedstocks With Mandates

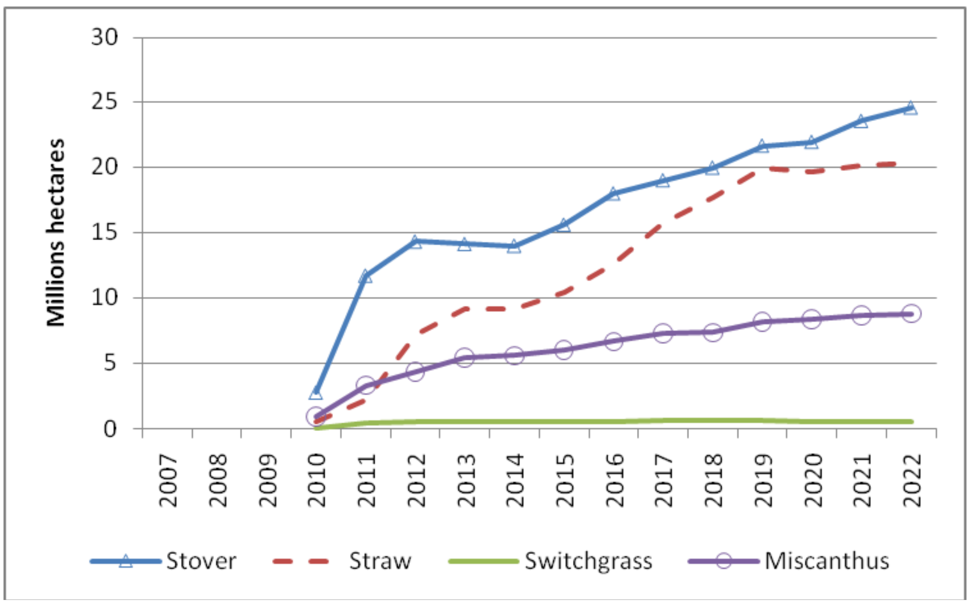

Figure 1b: Land Under Cellulosic Feedstocks With Mandates and Subsidies