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The Economic Potential of Second-Generation Biofuels: Implications for Social Welfare, Land Use and Greenhouse Gas Emissions in Illinois

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Xiaoguang Chen, Madhu Khanna and Hayri Önal¹

Abstract: This paper develops a dynamic micro-economic land use model that maximizes social welfare and internalizes externality from greenhouse gas emissions to obtain the optimal land use allocation for traditional row crops and bioenergy crops (corn stover, miscanthus and switchgrass), the mix of cellulosic feedstocks and fuel and food prices. We use this carbon tax policy as a benchmark to compare the implications of existing biofuel policies on land use, social welfare and the environment for the 2007-2022 period. The model is operationalized using yields of perennial grasses obtained from a biophysical model, county level data on yields of traditional row crops and production costs for row crops and bioenergy crops in Illinois. We show that a carbon tax policy that is directly related to carbon intensity of fuels can generate the highest social welfare among alternative policy scenarios. The existing ethanol tax credits result in substantial deadweight losses and higher GHG emissions as compared to the baseline. Ethanol blending mandates with subsidies lead to further welfare losses and higher GHG emissions. To meet advanced biofuel blending mandates, corn stover and miscanthus are used but the mix of viable cellulosic feedstocks varies spatially and temporally. Corn stover is viable mainly in central and northern Illinois while miscanthus acres are primarily concentrated on southern Illinois. The blending mandates lead to a significant shift in acreage from soybeans and pasture to corn and a change in crop rotation and tillage practices.

Key words: cellulosic ethanol, land use, social welfare, greenhouse gas emissions.
JEL: Q42, Q24

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Introduction

Biofuels are being increasingly viewed as a strategy to reduce reliance on foreign oil, to stabilize energy prices, mitigate global climate change and stimulate rural economic development in the U.S. Early energy policy in the U.S. sought to promote production and use of the first-generation biofuels, such as corn ethanol, through tax credits and import tariff. However, growing realization of the land competition created by corn-based biofuels and the implications of diverting corn for ethanol production on food prices has led to greater attention to second-generation biofuels from cellulosic feedstocks. Cellulosic ethanol also has much greater potential to reduce greenhouse gas (GHG) emissions than corn-based ethanol. The recently enacted Energy Independence and Security Act of 2007 (EISA) places mandates that 21 billion gallons of ethanol be produced from cellulosic feedstocks such as crop residues and perennial grasses (such as switchgrass and miscanthus) that have the potential to reduce GHG emissions by over 50%. In addition, the recent Farm Bill of 2008 provides considerable subsidies and incentives for cellulosic feedstocks.

From the perspective of social efficiency, government intervention in domestic markets is justified if it can reduce market failures caused by externalities. Government policies that seek to reduce GHG emissions should correct market prices to reflect their carbon intensity. Existing policy incentives such as biofuel tax credits and mandates are, however, not related to the carbon intensity of fuels and their welfare implications are not clear. This paper evaluates the competitiveness of biofuels from alternative feedstocks, their land use and GHG mitigation benefits in the absence of any government

intervention. We then examine the effects of biofuel subsidies and mandates on social welfare, land use, GHG emissions and nitrogen use.

We develop a dynamic spatial optimization model that determines the optimal land use choices to maximize social welfare that is the sum of consumers' and producers' surplus in fuel and food markets, subject to demand-supply balances, resource availability constraints, and technical constraints underlying production possibilities. Consumers obtain utility from vehicle miles traveled (VMT) that are produced by blending gasoline, corn ethanol and cellulosic ethanol. Gasoline and ethanol are imperfect substitutes in the production of VMT while corn ethanol and cellulosic ethanol are perfect substitutes. The model incorporates food and feed demand curves to obtain market equilibrium prices as endogenous variables. Spatial heterogeneity in yields, production costs for crops and land availability within a region are used to examine the heterogeneity in the viability of biofuels from alternative feedstocks across geographical locations and the optimal mix of feedstocks. Lifecycle analysis is used to estimate the externality costs of GHG emissions that are directly related to the type of fuel consumed and crops produced.

We use this framework to first analyze the first-best policies needed to correct the externality caused by VMT and crop production. Second, we compare the social welfare and environmental implications of alternative second-best policies, such as ethanol tax credits. Third, we explore the effects of binding biofuel mandates with ethanol and bioenergy feedstock subsidies. The model uses county-specific data for Illinois that is a major region for corn and soybean production in the U.S. to examine the economic and environmental implications of biofuel policies over the period of 2007-2022. Illinois has

the climatic and soil conditions that are suitable for perennials that can be used as feedstocks for cellulosic biofuels. Estimates of nitrogen use and life-cycle GHG emissions associated with biofuels from different feedstocks are based on county-specific production practices in the U.S.

Related Literature

Previous studies have examined impacts of existing domestic biofuel policies. Gallagher et al. (2003) analyze the implications of a renewable fuel mandate of 5 billion gallons of ethanol as a fuel additive with a conjunction of national MTBE ban on fuel prices and consumption, social welfare and the environment. They find that it decreases air pollution but raises the cost of the blended fuel considerably relative to baseline levels. This decreases gasoline consumption by 4% and social welfare (without considering environmental benefits) by 6% while raising corn price by 3%. Gardner (2007) compares the deadweight losses of an ethanol subsidy as compared to a deficiency payment policy that directly subsidizes corn. He estimates deadweight losses due to the ethanol subsidy to be 4 times in short run and 17 times in long run greater than those if a deficiency payment policy had been implemented instead. Environmental benefits of the ethanol subsidy would need to be valued at least at 23 cents per gallon of ethanol to offset the deadweight losses of the subsidy.

de Gorter and Just (2009) analyze the effects of a biofuel tax credit in the presence of a blend mandate while assuming that ethanol and gasoline are perfect substitutes. They show in the presence of the blend mandate a tax credit acts as a fuel consumption subsidy to increase gasoline consumption by 0.4% and corn price by 0.3%.

de Gorter and Just (2008) extend this work by incorporating an import tariff and find in the presence of a tax credit and an import tariff a binding ethanol mandate leads to an increase in domestic ethanol price by 6.6% in 2015. It also increases corn price by 13.4%.

Only a few studies examine the environmental impacts of existing and alternative biofuel policies. Vedenov and Wetzstein (2008) incorporate the environmental and fuel security externalities to show the optimal subsidy for ethanol should be \$0.22 per gallon since it improves fuel security valued at \$0.17 per gallon. Khanna, Ando and Taheripour (2008) examine the welfare effects of an ethanol subsidy while considering carbon emissions and congestion externalities caused by VMT. This framework is extended by Ando, Khanna and Taheripour (2009) and by Lasco and Khanna (2009) to examine the effects of a blend mandate and an import tariff with an ethanol subsidy, respectively. These papers show that existing biofuel policies are associated with large losses in social welfare relative to the optimal and with higher GHG emissions.

There are several studies that have examined the dynamics of agricultural land allocation between traditional row crops and bioenergy crops. Foremost among these are the studies based on the Forest and Agricultural Sector Optimization Model (FASOM) which is a multi-period, price endogenous, spatial market equilibrium land allocation model. Alig et al. (1997) and Alig et al. (2000) apply this model to investigate the implications of achieving given carbon sequestration targets and producing woody crops for the U.S. pulp and paper sector, respectively. McCarl et al. (2000) apply FASOM to examine the competitiveness of electric power generation using bioenergy from forest products and switchgrass instead of coal while disaggregating the U.S. into 11 homogenous regions. McCarl and Schneider (2001) expand this model into the

ASMGHG model to investigate competitiveness of various carbon mitigation strategies at alternative carbon prices across 63 regions in the U.S. They find that at low carbon prices, soil carbon sequestration through a change in cropping practices is competitive while at high carbon prices, abatement is achieved mainly through use of biomass for power generation and conversion of land to forests. Another dynamic agricultural sector model used to analyze allocation of cropland in the U.S. is POLYSYS (Ugarte et al. 2003). It is more regionally disaggregated than FASOM with 305 agricultural statistical districts as defined by the USDA. Walsh et al. (2003) apply POLYSYS to examine the potential for using CRP land to produce bioenergy crops at various bioenergy prices and find that switchgrass is more competitive than woody bioenergy crops. Using POLYSYS, English et al. (2008) show that the corn ethanol mandate will lead to major increases in corn production in the Corn Belt and shift in production regions for other crops over the period 2007-2016 (assuming that cellulosic biofuels are not feasible over this period). Malcolm (2008) uses Regional Environment and Agriculture Programming Model (REAP), a partial-equilibrium model of the U.S. agricultural sector consisting of 50 regions, to quantify the extent to which substitution of crop-residue based cellulosic ethanol for corn ethanol reduces soil erosion and nutrient deposition. Based on county-level data, Khanna et al. (2008) examines the implications of meeting pre-determined biofuel targets on cropland use and the optimal mix of cellulosic feedstocks in Illinois, and find that biofuel targets lead to a significant shift in crop rotation and tillage practices and miscanthus has more cost advantage than switchgrass in Illinois.

This paper differs from previous studies in several aspects. We extend our previous dynamic land use model (Khanna et al. 2008) by incorporating the fuel market

while considering alternative sources of bioenergy feedstocks such as corn, stover, miscanthus and switchgrass. We specify a constant elasticity of substitution (CES) production for miles from which fuel demands are obtained. Current studies assume that ethanol and gasoline are either perfect substitutes (de Gorter and Just 2008; de Gorter and Just 2009) or complete complements (Vedenov and Wetzstein 2008). Given current vehicle technology and the existence of E85 and E10, we model gasoline and ethanol as imperfect substitutes with a flexible substitution since it is too constraining to impose perfect substitutability or complete complements. Under alternative policy scenarios, we compare the competitiveness of alternative bioenergy feedstocks and analyze the optimal mix while recognizing temporal and spatial heterogeneity in returns to land at a county level rather than much broader regions considered in previous land use studies. Due to the perennial nature of miscanthus and switchgrass, we use a multi-period dynamic rolling horizon model. The model generates a time path of the costs under different policy scenarios and examines its sensitivity to assumptions about the processing cost of cellulosic ethanol and the production costs of cellulosic feedstocks.

Theoretical Framework

In this section, we examine the effects of a carbon tax on food and fuel consumption and land allocation. We consider an economy in which utility is produced from miles driven (m), food (f) and there is disutility from GHG emissions. Utility is additive and is given by the sub-utility functions $U=U(m)+U(f)$, where $U(m)=\int_0^m P(m)dm$ and $U(f)=\int_0^f P(f)df$. The sub-utility functions are assumed to be strictly increasing and concave. $P(m)$ and $P(f)$ are the market demand functions of miles

and food, and assumed to satisfy $P'(m) < 0$ and $P'(f) < 0$. To avoid corner solutions, we assume $\lim_{m \rightarrow \infty} P(m) = 0$, $\lim_{m \rightarrow 0} P(m) = \infty$, $\lim_{f \rightarrow \infty} P(f) = 0$ and $\lim_{f \rightarrow 0} P(f) = \infty$.

Fuels for vehicles consist of a flexible combination of gasoline and ethanol, denoted by g and e , respectively. A CES production function that relates m to g and e with constant returns to scale is assumed, $m(g, e) = \gamma[ag^\rho + (1-a)e^\rho]^{1/\rho}$, where $m'_g(g, e) > 0$, $m'_e(g, e) > 0$, $m''_{gg}(g, e) < 0$, $m''_{ee}(g, e) < 0$ and $m''_{ge}(g, e) > 0$. This function allows for flexibility in the degree of substitutability between gasoline and ethanol. The carbon 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, e , and assume food production is a clean technology and does not generate GHG emissions. We relax these assumptions in the empirical model. Aggregate GHG emissions are, therefore, equal to $\delta_g g + \delta_e e$. The carbon tax is given by t .

For simplicity, we assume land is homogenous in quality and its endowment is denoted by \bar{L} . Let the portion of land dedicated to the production of food and ethanol be L_f and L_e , respectively. Without loss of generality, both the outputs of food and ethanol per unit of land can be normalized to one, so $L_f = f$ and $L_e = e$. The land used to produce food and ethanol should be less than the total land availability, $\bar{L} - f - e \geq 0$. The costs of producing food and fuels are assumed to be strictly convex, denoted by $c(i)$, $i \in \{g, e, f\}$. The cost $c(e)$ includes the conversion cost of food to ethanol. We assume marginal cost of ethanol is greater than that of gasoline, $c'(e) > c'(g)$.

The social planner determines the welfare-maximizing choice of fuel and food production while taking into account the externality cost of carbon emissions by solving the following problem:

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

$$\text{subject to } m = r[ag^\rho + (1-a)e^\rho]^{1/\rho} \text{ and } \bar{L} - f - e \geq 0.$$

The Lagrangian is:

$$l = U(m(g,e)) + U(f) - t(\delta_g g + \delta_e e) - c(g) - c(e) - c(f) + \lambda(\bar{L} - f - e) \quad (1)$$

and the first order conditions are:

$$\frac{\partial l}{\partial g} = 0 \Leftrightarrow \frac{\partial U(m)}{\partial g} - \delta_g t - c'(g) = 0 \quad (2)$$

$$\frac{\partial l}{\partial e} = 0 \Leftrightarrow \frac{\partial U(m)}{\partial e} - \delta_e t - c'(e) - \lambda = 0 \quad (3)$$

$$\frac{\partial l}{\partial f} = 0 \Leftrightarrow U'_f(f) - c'(f) - \lambda = 0 \quad (4)$$

where λ is the Lagrangian multiplier and measures land rent.

Equation (2) implies that it is optimal to choose the gasoline consumption when marginal benefit obtained from gasoline is equal to its production cost plus its externality cost. Similarly, equation (3) shows marginal benefit from ethanol should be equal to its production cost plus externality cost and land rent. Equation (4) illustrates that the optimal food consumption occurs when the marginal benefit of food equals its production cost plus land rent. In a market economy, consumers will not consider externality costs in their consumption decisions. To induce the optimal outcomes, equation (2) and (3) suggest environmental taxes should be levied on fuels based on their carbon intensity.

The marginal utility from fuels is obtained from their contribution to the production of miles that generate utility. Equation (2) (3) and (4) together imply the relative consumption of gasoline and biofuels depends on their marginal costs and the net marginal benefit of food, as shown in equation (5).

$$\left(\frac{g}{e}\right)^{\rho-1} = \frac{\delta_g t + c'(g)}{\delta_e t + c'(e) + U'(f) - c'(f)} \frac{1-a}{a} \quad (5)$$

The carbon tax increases the marginal costs of fuels and the ratio of the marginal cost of gasoline to ethanol since gasoline is more carbon intensive than ethanol. Therefore it is straightforward to derive $d(g/e)/dt < 0$ (see Appendix 1) from (5). Further insight into the properties of the optimal solutions can be gained from the following comparative static analysis from the first order conditions (2)-(4) (See Appendix 2).

$$\frac{dg}{dt} < 0 \quad (6a)$$

$$\frac{de}{dt} = \frac{p(m)(\delta_e m_g - \delta_g m_e)}{g} \left(\frac{E_{mg}}{\varepsilon_m} + \varepsilon_{\delta_g m_e - \delta_e m_g} \right) - \frac{\delta_e c'(g)}{s_g g} \quad (6b)$$

$$\frac{df}{dt} = -\frac{de}{dt}, \text{ and } \frac{d\lambda}{dt} = (c''(f) - U''_{ff}) \frac{de}{dt} \quad (6c)$$

$$\frac{dg}{dL} < 0 \quad \text{if } \varepsilon_m > -\sigma_m \quad (6d)$$

$$\frac{df}{dL} > 0, \frac{de}{dL} > 0 \text{ and } \frac{d\lambda}{dL} < 0 \quad (6e)$$

where $p(m)$ is the price of miles, which depends upon the marginal costs of fuels; ε_m , E_{mg} , s_g are demand elasticity of miles, output elasticity of miles with respect to gasoline, and gasoline supply elasticity, respectively. We define m_g and m_e as the marginal productivity of fuels in producing miles (which can be interpreted as fuel efficiency) with $m_e > m_g$ due

to the assumption of $c'(e) > c'(g)$ (See Appendix 2). Moreover, from the property of the CES production function of miles, we know an increase in gasoline consumption leads to a decrease in m_g and an increase in m_e . We define $\mathcal{E}_{\delta_g m_e - \delta_e m_g}$ as the elasticity of the difference in fuel efficiency due to the change in gasoline consumption.

From (6a), we show that imposing a carbon tax always reduces the gasoline consumption. Equation (6b) illustrates that the change in ethanol with the carbon tax depends upon the magnitudes of a variety of parameters, such as carbon intensity of fuels, the demand elasticity of miles, the supply elasticity of gasoline and the elasticity of substitution between gasoline and ethanol. Equation (6c) shows that due to the limited land endowment the land allocated to food decreases while the land rent increases with an increase in ethanol, respectively. From (6d), we find that gasoline consumption decreases with increased land availability when miles demand is inelastic and the substitution between fuels is high. Finally, (6e) demonstrates that increasing the land availability raises land allocated to both ethanol and food production and decreases land rent.

We now examine the impacts of alternative parameters on the optimal choices graphically. Given a demand curve for miles D_m in Figure (1a) and marginal cost curves for gasoline MC_g and ethanol MC_e in Figure (1b) and (1c), the optimal consumption of M^0 , g^0 and e^0 are determined by maximizing utility (in the absence of the carbon tax). This also results in demand curves for gasoline D_g and ethanol D_e , and a marginal cost curve for miles, MC_m . Internalization of the emission cost shifts the marginal cost curves of fuels to the left to MC_g^t and MC_e^t with the former likely to shift further to the left than the latter since gasoline is more carbon intensive than ethanol. Subsequently, the marginal cost of miles shifts to the left to MC_m^t , and miles driven decreases to $M^* < M^0$. If

miles demand is considerably inelastic ($\epsilon_m \approx 0$) and gasoline price is fixed ($s_g = \infty$), gasoline price increases by its marginal externality cost $t\delta_g$ in Figure (1b), which in turn leads to an increase in the miles price. However since miles demand is inelastic, the carbon tax only results in a slight reduction in VMT as shown in Figure (1a). Substitution effect of ethanol to gasoline is expected to be greater than the miles effect as shown in Figure (1e). The change in VMT in turn generates a subsequent effect on fuel demand curves, which shifts the demand curve for gasoline to the left to D_g^t , and the demand curve for ethanol to the right to D_e^t . Optimal fuels consumption are, therefore, $g^* < g^0$ and $e^* > e^0$ and optimal miles driven is $M^* < M^0$. As the demand for ethanol increases, land rent increases from λ^0 to λ^* as shown in Figure (1d).

Now we consider another case in which gasoline supply is inelastic and miles demand is elastic ($\epsilon_m \approx -\infty$). In this case, VMT significantly decrease due to its increased marginal cost and elastic demand curve. Gasoline consumption does not decline much because of its inelastic supply curve. In this case the miles effect is likely to be greater than the substitution effect of ethanol to gasoline as shown in Figure (2e). Accordingly, demand curves for fuels shift to the left in Figure (2b) and (2c). Optimal consumption of fuels is less than the levels under no-intervention while less competition for land lowers the food price and land rent as shown in Figure (2d). However, under both cases, total GHG emissions decline since gasoline and ethanol are functions of carbon tax; thus $dGHG/dt < 0$ (see Appendix 3).

Non-Optimal Biofuel Policies

We now consider the case where a carbon tax is not implemented and instead alternative biofuel policies are developed and examine their effects on food and fuel markets.

Blend Mandate

A blend mandate requires a minimum share of biofuel β in mixed fuel sold, where $0 < \beta < 1$. Under this policy, there is no carbon tax on fuels. We refer to the case where the carbon tax $t=0$, and the ratio of ethanol to total fuel is $e/(e+g)=\beta$. Such a policy encourages production and consumption of biofuel because it increases the biofuel share in fuel consumption relative to the level with non-intervention. The consumption of ethanol and gasoline is likely to be higher and lower, respectively, than that with non-intervention. Imposing the blend mandate shifts ethanol demand curve to the right to D_e^B and gasoline demand curve to the left to D_g^B as shown in Figure (3c) and (3b). In Figure (3a), an increase in the blend mandate of β is likely to result in a higher marginal cost of miles and will shift the marginal cost curve of miles to the left to MC_m^B . The decreased VMT in turn adjusts the fuel consumption to comply with the mandate as shown in Figure (3e). However, as shown in Appendix 4 the fuel consumption depends upon the elasticity of miles demand curve. Intuitively, if miles demand is inelastic, the miles effect is expected to have a small impact on fuel consumption and the substitution effect between fuels will be dominant. Then we have $e^B > e^0$, $f^B < f^0$ and $g^B < g^0$. Accordingly, land rent increases as shown in Figure (3d). But if the miles demand is elastic, the opposite results would be obtained.

de Gorter and Just (2009) argued that an increase in β is possible to lower the consumer price of miles if the gasoline supply is elastic relative to ethanol. That is because the gasoline price would drop significantly as the demand for gasoline decreases, which is possible to offset the increase in ethanol price to lower the marginal cost of miles. Therefore, an elastic gasoline supply curve further increases the consumption of miles, which in turn increases the demand for ethanol.

Blend Mandate and a Subsidy on Ethanol

Current US biofuel policy gives a \$0.45 per gallon for corn ethanol and 2008 farm bill proposes a \$1.01 per gallon for cellulosic ethanol to promote ethanol production. We now analyze impacts of ethanol subsidy when the blend mandate is in place. The subsidy encourages more ethanol consumption and VMT because it lowers the marginal cost of ethanol, which in turn decreases the marginal cost of miles. Graphically, this subsidy shifts the supply curve of ethanol from MC_e to the right to MC_e^s in Figure (3c). It is also likely to shift marginal cost curve of miles from MC_m^B to the right to MC_m^s in Figure (3a), the extent to which depends upon the level of subsidy. Reduced cost leads to an increase in VMT, which is expected to raise the consumption of both fuels since the blend mandate does not allow substitutability between them. Gasoline demand increases and its demand curve shifts from D_g^B to the right to D_g^E as shown in Figure (3b). This ethanol subsidy is likely to lead to a reduction in food consumption and an increase in land rent as shown in Figure (3c).

Hence, when a binding blend mandate is in place the ethanol subsidy leads to increases in the consumption of fuels, VMT and carbon emissions and a decrease in the social welfare. Appendix 4 shows the impacts of this ethanol subsidy in the presence of

the blend mandate: $\frac{dg}{ds} > 0$, $\frac{de}{ds} > 0$, $\frac{df}{ds} < 0$, $\frac{d\lambda}{ds} > 0$ and $\frac{dGHG}{ds} > 0$. Further, we

examine cross effects of the subsidy and the blend mandate, we find $\frac{d^2e}{d\beta ds} > 0$,

$$\frac{d^2g}{d\beta ds} < 0, \frac{d^2f}{d\beta ds} < 0 \text{ and } \frac{d^2\lambda}{d\beta ds} > 0.$$

Empirical Model

We take the dynamic spatial optimization model developed in Khanna et al. (2008) as our starting point to analyze optimal land use strategies, fuel consumption, and production and consumption of various row crops and perennial crops under different policy scenarios while maximizing the sum of discounted consumers' and producers' welfare in fuel and food markets in Illinois over the 16-year planning horizon of 2007-2022.² This paper extends the previous model by taking into account fuel market by assuming consumers obtain utility from VMT that are produced by blending gasoline, corn ethanol and cellulosic ethanol. Gasoline and ethanol are imperfect substitutes in the production of VMT while corn ethanol and cellulosic ethanol are perfect substitutes. Miles consumers' behavior is represented by a constant elasticity demand curve while we assume a CES production function for VMT.

The key assumptions for this paper are summarized as follows. The model considers the returns from the sales of co-products of corn ethanol production, DDGs, which are assumed to be a perfect substitute for feed corn based on their conversion rate. Since Illinois is a relatively small consumer of gasoline, we use a fixed gasoline price

² See Khanna et al (2008) for rigorous model description.

during the planning horizon. Corn yield is assumed to increase 1.8 bushel per year while the yields of other crops remains constant over time. The blending mandates over time in Illinois are assumed to be the same as the national level while the blending mandates beyond 2022 are being set at their levels in 2022.

Data and Parameters

We apply this model in Illinois using county-specific data to examine the economic and environmental implications of alternative ethanol policies. We assume constant elasticity demand curves for miles and food and feed with an elasticity of -0.4 for VMT demand (Parry and Small 2005; Vedenov and Wetzstein 2008).³ To parameterize the demand of food and miles for future years, we assume demand for corn, soybeans and miles increase by 0.86%, 0.96% and 2.5% each year after 2007.⁴

We assume the elasticity of substitution in the CES production function increases gradually from 2 in 2007 to 10 in 2022 to capture the potentially increased substitutability between ethanol and gasoline. The related parameters for this CES production function are calibrated using 2007 market data. The Federal Highway Administration (FHWA) reports that total vehicle-miles traveled in 2007 were 107.5 billion in Illinois while the Energy Information Administration (EIA) reports that 4.7 billion gallons of gasoline and 0.44 billion gallons of ethanol were consumed in Illinois for transportation use in 2007. Since Illinois is a relatively small consumer of gasoline, we fix the gasoline price as \$2.38 per gallon in 2007 price in this model.⁵ We calibrate the market price of ethanol as the wholesale rack price for corn ethanol plus fuel tax and per gallon net return in

³ See Khanna et al (2008) for deriving regional food demand curves.

⁴ FAPRI (2008) and www.fhwa.dot.gov/environment/vmt_grwt.htm#4foot;
http://www.fhwa.dot.gov/environment/vmt_grwt.htm#4foot

⁵ gas price: http://tonto.eia.doe.gov/dnav/pet/pet_pri_allmg_c_SIL_EPM0_cpgal_a.htm

refinery and a \$0.13 per gallon markup yielding \$2.52 per gallon for corn ethanol in 2007. Similarly, we compute the consumer price of ethanol by using farm-gate production cost of ethanol per gallon plus the net return in refinery and the markup for the planning horizon. Here, the net return for ethanol refinery is assumed to be 7% of equity investment, which is \$0.07 and \$0.29 per gallon for corn ethanol and cellulosic ethanol, respectively.

We consider corn, soybeans, wheat and sorghum as the annual crops while alfalfa, switchgrass and miscanthus are considered as the perennial crops. Cellulosic ethanol can be produced from switchgrass, miscanthus and corn stover. We estimate county- specific rotation and tillage production costs in 2007 prices for four row crops—corn, soybeans, wheat and sorghum—and three perennial grasses—alfalfa, switchgrass and miscanthus. Corn stover yield and production costs are also estimated by alternative rotations and tillages (Sheehan et al. 2003). We conduct a life cycle analysis of the above ground CO₂ equivalent emissions (CO₂e) generated from biofuels production using different feedstocks; the major GHG emissions are converted to equivalent levels based on their 100-year global warming potential (IPCC 2001). We include the CO₂e generated not only from various inputs and machinery used on the farm in the production of each feedstock and the energy used to produce and transport those inputs to the farm, but also from the energy used to transport the feedstock to a biorefinery and the energy used to convert the feedstock to biofuel. Detailed description about crop production costs and carbon emissions associated with crop production and ethanol conversion can be found in Khanna et al. (2008).

As a major exporter of ethanol, we assume Illinois exports 50% of its ethanol production under all scenarios except the scenarios under the blend mandates. This percentage is derived based on observed ethanol consumption and production in Illinois in 2007. We follow the method proposed by the Environmental Protection Agency (EPA) to estimate the blend mandates in Illinois for the 16 years.⁶ Specifically, we first compute total fuel consumption using projected national miles consumption that is estimated using the miles consumption in 2007 multiplied by 2.5% per year. Then we calculate the energy equivalent value needed for the projected national miles consumption while assuming a constant fuel efficiency of 17.2 miles per gallon.⁷ Based on energy equivalent value of ethanol to gasoline that is 1 gallon of ethanol is equivalent to 2/3 gallon of gasoline and RFS' ethanol consumption mandates, we obtain separate blending mandates for corn ethanol and cellulosic ethanol in total fuel consumption for the planning horizon of 2007-2022. Since the CES function degenerates to a linear function of fuels under the blend mandates, the above approach of deriving the blend mandates, therefore, is consistent with our model setup. In addition, under the blending mandates we assume Illinois produces 18.8% of the RFS corn ethanol mandate, and exports 9% of the RFS cellulosic ethanol mandate.

Finally, as proposed by the recent Farm Bill (2008), the tax credits for corn ethanol and cellulosic ethanol are \$0.45 and \$1.01 per gallon while eligible cellulosic biomass is subsidized by \$45 per ton for the first two years after establishment. We account for a fuel tax of \$0.387 per gallon on fuels.

⁶ Revised Renewable Fuel Standard for 2008, Issued Pursuant to Section 211(o) of the Clean Air Act as Amended by the Energy Independence and Security Act of 2007.

⁷ <http://www.fhwa.dot.gov/policy/ohim/hs06/htm/vm1.htm>

Results

We simulate the fuel and food consumption and land use decision under five different scenarios: no intervention (baseline), carbon tax, status-quo tax credits and blend mandates without and with subsidies. The fuel tax of \$0.387 per gallon is imposed on both gasoline and ethanol in all scenarios. We report land use decision, commodity consumer and producer prices and quantities, environmental and social welfare effects for the various scenarios. Social welfare is the sum of discounted producers' and consumers' surplus over 16 years' planning horizon while the environmental effects are also accumulative over the same period. In the welfare section, we compute the welfare change for each scenario relative to the baseline, and decompose it into the changes from miles consumption, crop production and consumption, government revenue and environmental externality.

No Intervention (Baseline)

We simulate the baseline scenario where there is no biofuel or carbon policy. In this scenario, gasoline consumption is about 7 B gallons in 2022 and VMT is 147 B miles. Of the total fuel consumption, ethanol accounts for 0.4 B gallons while the ratio of ethanol in total fuel consumption is only 0.6%. Only 1% of corn production is used for ethanol production while corn price is \$4.1 per bushel and land rent is \$342 per acre. Total GHG emissions are 0.77 M tons in this scenario and gasoline contributes 91% since it has a large share in total fuel consumption. Nitrogen use is 15.1 thousand tons.

Carbon Tax

Next we examine the effects of a carbon tax of \$34 per ton, a carbon price expected to prevail in the near future⁸. As compared to the baseline, VMT decreases by 5% (from 147 B miles to 141 B miles) due to the carbon tax while raising social welfare by \$0.7 B. In this scenario, only corn ethanol is produced since cellulosic ethanol is still more costly than corn ethanol while gasoline consumption decreases by 8% relative to the baseline. Increased ethanol production raises the ratio of ethanol to total fuel consumption in 2022 to 4.7%. Due to increased ethanol production and cropland competition, corn price and land rent are 3% and 2% higher than that in the baseline, respectively. GHG emissions reduce by 3% while nitrogen use increases by 0.3% relative to the baseline.

Status-quo

In this scenario, we assume that existing biofuel policies prevail and that there is a subsidy of \$0.45 per gallon and \$1.01 per gallon for corn ethanol and cellulosic ethanol, respectively. This policy intends to encourage cellulosic ethanol production as a substitute for corn ethanol and gasoline to reduce GHG emissions. It leads to a large increase in ethanol consumption of 0.7 B gallons in 2022 relative to the baseline. As compared to the baseline, gasoline consumption declines by 8% while VMT remain the same due to an inelastic miles demand. The ratio of ethanol to total fuel consumption increases to 10%. Of the total corn production in 2022, 23% is used for ethanol production, which in turn reduces the quantity of corn for food and feed consumption and leads to an increase in corn price by 7% and land rent by 6%, respectively, relative to the baseline levels. The policy of status-quo reduces GHG emissions by 1% but increases

⁸ <http://www.euractiv.com/en/climate-change/european-co2-emissions-2007/article-171327>

nitrogen use by 2% as compared to the baseline. Due to government spending and consumer welfare losses, social welfare is \$0.8 B less than the baseline.

Land Use Implications for Non-Mandate Scenarios

Under all scenarios aside from blend mandates, we find there are insignificant effects on land use outcomes due to a relatively small quantity of ethanol production. Of the total cropland, the acreages allocated to corn and soybeans change from 49% and 44% under the baseline to 50% and 43% under the status-quo, while the share of conservation tillage varies from 37% under the carbon tax policy to 42% under the baseline. The land under corn-soybean rotation and corn-corn rotation ranges from 70% and 14% under the carbon tax policy to 80% and 9% under the baseline. However, under these scenarios, no cropland is allocated to corn stover and dedicated energy crops due to their high production costs.

Blend Mandates

The effect of the blend mandates without subsidy on ethanol and bioenergy crops is simulated in this scenario. The ratio of ethanol to total fuel consumption increases to 14% due to the blending mandates. This policy also leads to an increase in ethanol consumption at 0.41 B gallons and 0.58 B gallons of cellulosic ethanol. It has the lowest demand for gasoline at 6.15 B gallons with a reduction by 12% relative to the baseline.

The diversion of land to biofuel production affects the prices of both corn and soybeans because of the reduced acreage and consumption of these commodities for food and feed uses, as shown in Figure 4. In particular, the blend mandates require 45% of the total corn production used for ethanol, which increases corn price by 14% (from \$4.1 per bushel to \$4.7 per bushel) relative to the baseline. Soybeans production decreases by 16%

(from 0.44 B bushels to 0.37 B bushels) and price increases by 2% (from \$10.9 per bushel to \$11.1 per bushel). Compared to the baseline, land rent increases by 11% (from \$342 per acre to \$379 per acre).

Since ethanol has a small share in the total fuel consumption, the increase in ethanol use cannot offset the reduction in GHG emissions due to decreased use of gasoline. GHG emissions decrease slightly by less than 1% while increasing nitrogen use by 13% relative to the baseline. Social welfare decreases by \$2.3 B relative to the baseline due to forgone income from taxes, externality cost and deadweight losses caused by sub-optimal options.

Imposing blend mandates has three types of effects on land use. First and foremost, it leads to a conversion of land from food crops to biofuel crops. The results show an increase in the percentage of land under corn (from 49% to 54%) and a decrease in the percentage of land under soybeans (from 44% to 38%), wheat (from 3% to 2.9%) and pasture (from 2.2% to 1.7%) relative to the baseline. Of the total cropland, 4.5% will be allocated to miscanthus production while switchgrass will not be produced due to its low yield and cost disadvantage compared to miscanthus. All available corn stover will be collected for cellulosic ethanol production in 2022. The trends in acreages under corn, soybeans, corn stover and miscanthus are shown in Figure 5. We find corn stover and miscanthus will be used conjunctively to produce biofuels. Specifically, 33% of cellulosic ethanol in 2022 will be produced from miscanthus.

Second, we observe a dramatic change in rotation and tillage practices under the blend mandates. In particular, the percentage of cropland under conservation tillage increases from 42% to 57% for the ease of collecting corn stover relative to the baseline.

The cropland under corn-soybean rotation decreases from 80% to 47% relative to the baseline while the cropland under corn-corn rotation increases from 9% to 31%.

Third, we also find a considerably spatial variability in the land converted to cellulosic feedstocks across counties and over time under this scenario. In 2015, 82% of corn acreage will be in the central and northern Illinois while corn stover will be collected in 40 of 102 counties in those regions. In contrast, all available corn stover will be collected including counties in southern Illinois for cellulosic ethanol production in 2022 as shown in Figure 6. Miscanthus production will occur until 2016 when all available corn stover cannot meet the blend mandate with 15 counties allocating about 8.5 thousand acres. Towards the end of the planning horizon 41 of the 102 countries will allocate 5% of their total cropland to miscanthus production, which is primarily concentrated in the southern counties.

Blend Mandates with Subsidies

We simulate the effects of blend mandates with corn ethanol subsidy of \$0.45 per gallon, cellulosic ethanol subsidy of \$1.01 per gallon and \$45 per metric ton on biomass in this scenario. This policy shows insignificant impacts on land use and commodity production and prices relative to the scenario under the blend mandates without subsidies. However, due to the subsidies for ethanol production, the consumer price of corn and cellulosic ethanol decline by 18% (from \$2.4 per gallon to \$2 per gallon) and 37% (from \$3 per gallon to \$1.9 per gallon), respectively, as compared to the mandates scenario without subsidies. That in turn increases VMT by 1% (2 B miles) while raising gasoline consumption by 1% relative to the mandates without subsidies. Accordingly, GHG emissions increase by 1%. Since it induces a significant amount of government expense

and externality cost, this policy is the most welfare-reducing policy with \$3.3 B losses relative to the baseline.

The welfare estimates in this paper provide an idea of how large the environmental and energy security benefits should be to justify the ethanol subsidy and mandates. In the planning horizon of 16 years, the cumulative additional production of ethanol is about 6.4 billion gallons relative to the baseline. Therefore, if the ethanol policies are to create a net social welfare gain, external benefits of each gallon of ethanol should be valued at least at \$0.51 per gallon of ethanol.

Sensitivity Analysis

We examine the sensitivity of our results to the processing cost of cellulosic ethanol, low production costs of dedicated bioenergy grasses with high yields (low cost) and high production costs of dedicated bioenergy grasses with low yields (high cost). Table 2 shows the results under the mandate scenario relative to the baseline. We find that reducing the processing cost of cellulosic ethanol gradually from \$1.76 per gallon in 2007 to \$0.7 per gallon in 2022 decreases the consumer price of cellulosic ethanol by 60% (from \$1.89 per gallon to \$0.77 per gallon) as compared to the mandates with subsidies. As a result, it lowers the consumer price of miles, which leads to an increase in VMT by 1% (about 2 B miles) relative to the mandates with subsidies.

The changes in the production costs and harvesting yields of dedicated energy crops have a small impact on land allocation. In the low cost scenario, the percentage of land under miscanthus increases by 0.5% relative to the mandates and stover is collected on 96% of available corn acres. That is because miscanthus becomes more competitive than stover in producing cellulosic ethanol under this assumption. In the high cost

scenario, we find that the land under miscanthus instead increases by 1.6% (from 4.7% to 6.3%) while all available stover is collected for cellulosic ethanol production, although miscanthus becomes less competitive. This is because the binding mandates will require more land allocated to miscanthus given its low yield and limited availability of corn stover.

Concluding Remarks

Energy security and environmental concerns stimulate the current biofuel policies. This article develops a dynamic spatial optimization land use model to analyze the implications of prevailing biofuel policies on land allocation among food and fuel crops, social welfare and the environment. Although this study has a narrow geographical focus, our main conclusions are similar to those obtained by stylized models using a similar framework and applied to the U.S. as a whole (Ando, Khanna and Taheripour 2009; Khanna, Ando and Taheripour 2008). We find existing ethanol tax credits result in substantial deadweight losses and an increase in GHG emissions relative to the baseline. The ethanol mandates with subsidies would lead to further welfare losses and an increase in GHG emissions.

Our results support the use of a carbon tax to correct the externality caused by fuel consumption, but not an ethanol subsidy. A subsidy increases the use of ethanol which emits less GHG than gasoline, but the benefits of reduced GHG emissions are not enough to offset the deadweight losses of the subsidy. We find that the blend mandates with subsidies lead to an increase in VMT and gasoline, which in turn increases GHG emissions relative to the baseline. The demand for corn ethanol also results in 54% of land allocated to corn production, which is a nitrogen-intensive technology. Accordingly,

water quality would become worse. Since the blend mandates with subsidies induces significant government payments and externality cost, it is the most welfare-reducing policy. It also results in a significant shift in the acreage from soybeans, wheat and pasture to corn, and a change in crop rotation and tillage practices as compared to the baseline. Despite an increase in corn production by 6%, the blending mandates would lead to considerable increases in corn and soybeans prices. Among cellulosic feedstocks, corn stover is likely to be used for cellulosic ethanol production in initial years. However all available corn stover is insufficient to meet the targets. This makes miscanthus as an inevitable alternative source of bioenergy while switchgrass is not competitive as compared to miscanthus due to its relatively low yields in the study region. There is a considerably spatial variability in the allocation of land to food and fuel crops across Illinois. Corn and stover production would occur in central and northern Illinois while miscanthus production is primarily concentrated in the southern counties.

Sensitivity analysis presented here shows that the effects of biofuel mandates on land allocation, GHG emissions and social welfare are not sensitive to the technology improvement in refineries plants and assumed variation in the production costs and harvesting yields of dedicated energy crops.

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Table 1. Results of Ethanol Policies on Land Use, Crop Production, the Environment and Welfare in 2022

	Baseline ^a	Carbon Tax	Status Quo ^b	Blend Mandates	Blend Mandate with Subsidies ^c
Policy Inventions					
Corn ethanol subsidy (\$/gallon)	0.00	0.00	0.45	0.00	0.45
Cellulosic ethanol (\$/gallon)	0.00	0.00	1.01	0.00	1.01
Carbon tax (\$/ton)	0.00	34.00	0.00	0.00	0.00
Biomass subsidy (\$/ton)	0.00	0.00	0.00	0.00	45.00
Land Use					
Total land (M Acres)	22.40	22.41	22.43	22.46	22.46
Corn (%)	49.03	49.35	50.43	54.47	53.96
Soybeans (%)	44.13	43.97	43.12	37.70	38.11
Wheat(%)	3.00	3.01	3.06	2.88	2.81
Pasture(%)	2.17	2.07	2.00	1.67	1.68
Stover (%)	0.00	0.00	0.00	54.47	53.96
Miscanthus (%)	0.00	0.00	0.00	4.53	4.66
Conservation tillage(%)	42.18	37.22	40.91	57.01	56.32
Corn-soybean rotation (%)	80.24	70.26	77.48	46.61	48.85
Corn-corn rotation (%)	8.91	14.22	11.68	31.17	29.53
Consumer Prices					
Miles (\$/mile)	0.113	0.125	0.112	0.119	0.112
Corn ethanol (\$/gallon)	2.29	2.51	1.90	2.43	1.99
Cellulosic ethanol (\$/gallon)				3.03	1.89
Corn (\$/bushel)	4.11	4.22	4.39	4.68	4.74
Soybean (\$/bushel)	10.85	10.85	10.89	11.12	11.12
Land rent (\$/acre)	342.24	347.56	363.41	379.00	378.35
Quantities (B Bushels/ Miles/Gallons)					
Corn Production	2.07	2.08	2.11	2.26	2.24
Corn Consumption (non-ethanol use)	2.04	1.85	1.62	1.25	1.23
Soybeans	0.44	0.44	0.43	0.37	0.37
Miles	147.574	141.448	147.574	147.574	149.616
Gasoline Consumed	6.96	6.42	6.37	6.15	6.24
Corn Ethanol Consumed	0.04	0.31	0.71	0.41	0.42
Cellulosic Ethanol Consumed	0.00	0.00	0.00	0.58	0.59
Corn Ethanol Produced	0.09	0.63	1.38	2.82	2.82
Stover Ethanol Produced	0.00	0.00	0.00	1.79	1.78
Miscanthus Ethanol Produced	0.00	0.00	0.00	0.85	0.87
Ethanol/fuel (%)	0.60	4.49	10.07	13.94	13.94
Environmental and Welfare Effects					
Greenhouse Gas Emissions (M tons)	0.771	0.734	0.761	0.775	0.783
Nitrogen (1000 tons)	15.101	15.146	15.417	16.990	16.955
Change in Total Welfare (\$B)	0.00	0.65	-0.82	-2.34	-3.27
Change in Miles Consumers' Surplus (\$B)	0.00	-25.54	2.35	-5.14	0.99
Change in Crop Consumers' Surplus (\$B)	0.00	-1.38	-5.25	-15.09	-15.18
Change in Crop Producers' Surplus (\$B)	0.00	1.42	5.86	18.02	18.14
Change in Government Revenue (\$B)	0.00	24.89	-4.11	0.00	-6.84
Change in Externality Cost (\$B)	0.00	1.26	0.34	-0.12	-0.39

^a There is no biofuel policy or carbon tax.

^b \$0.45 per gallon and \$1.01 per gallon subsidies on corn ethanol and cellulosic ethanol, respectively.

^c Besides the subsidies on ethanol there is a subsidy of \$45 per ton on biomass.

Table 2. Results Under Blending Mandates with Cost and Yield Changes

	Reduced Processing Cost of Cellulosic Ethanol	Low Cost	High Cost
Land Use			
Total land (M Acres)	22.46	22.46	22.46
Corn (%)	53.96	53.51	54.14
Soybeans (%)	38.08	38.43	37.08
Wheat(%)	2.80	2.70	2.72
Pasture(%)	1.68	1.65	1.66
Stover (%)	53.96	51.44	54.14
Miscanthus (%)	4.70	5.16	6.25
Conservation tillage(%)	56.33	55.38	55.94
Corn-soybean rotation (%)	52.61	52.97	46.11
Corn-corn rotation (%)	27.65	27.02	31.09
Consumer Prices			
Miles (\$/mile)	0.109	0.113	0.114
Corn ethanol (\$/gallon)	1.99	1.99	1.99
Cellulosic ethanol (\$/gallon)	0.77	1.75	2.02
Corn (\$/bushel)	4.74	4.74	4.74
Soybean (\$/bushel)	11.12	11.12	11.16
Land rent (\$/acre)	378.73	350.91	393.17
Quantities (B Bushels/ Miles/Gallons)			
Corn Production	2.24	2.22	2.24
Corn Consumption (non-ethanol use)	1.23	1.22	1.24
Soybeans	0.37	0.38	0.36
Miles	151.659	149.616	149.616
Gasoline Consumed	6.32	6.24	6.24
Corn Ethanol Consumed	0.43	0.42	0.42
Cellulosic Ethanol Consumed	0.60	0.59	0.59
Corn Ethanol Produced	2.82	2.82	2.82
Stover Ethanol Produced	1.78	1.72	1.78
Miscanthus Ethanol Produced	0.87	0.93	0.86
Ethanol/fuel (%)	13.94	13.94	13.94
Environmental and Welfare Effects			
Greenhouse Gas Emissions (M tons)	0.788	0.788	0.783
Nitrogen (1000 tons)	16.956	16.796	16.984
Change in Total Welfare (\$B)	-0.96	-4.17	-3.82
Change in Miles Consumers' Surplus (\$B)	3.52	1.13	0.90
Change in Crop Consumers' Surplus (\$B)	-15.18	-15.15	-15.24
Change in Crop Producers' Surplus (\$B)	18.14	17.55	17.82
Change in Government Revenue (\$B)	-6.89	-7.12	-6.90
Change in Externality Cost (\$B)	-0.56	-0.57	-0.40

Appendix 1: Proof of Equation (5)

$$\left(\frac{g}{e}\right)^{\rho-1} = \frac{\delta_g t + c'(g)}{\delta_e t + c'(e) + U'(f) - c'(f)} \frac{1-a}{a} \quad (5)$$

$$\frac{g}{e} = \left[\frac{\delta_g t + c'(g)}{\delta_e t + c'(e) + U'(f) - c'(f)} \frac{1-a}{a} \right]^{\frac{1}{\rho-1}}$$

$$\frac{d(g/e)}{dt} = \frac{1}{\rho-1} \cdot \left[\frac{\delta_g t + c'(g)}{\delta_e t + c'(e) + U'(f) - c'(f)} \frac{1-a}{a} \right]^{(2-\rho)/(\rho-1)} \left(\frac{1-a}{a} \right) \frac{\delta_g (c'(e) + U'(f) - c'(f)) - \delta_e c'(g)}{\{\delta_e t + c'(e) + U'(f) - c'(f)\}^2}$$

Since $\delta_g > \delta_e$, then we have

$$\delta_g (c'(e) + U'(f) - c'(f)) - \delta_e c'(g) > \delta_g (c'(e) + U'(f) - c'(f) - c'(g)) > 0$$

$$\text{So, we get } \frac{d(g/e)}{dt} < 0. \quad (\text{A1})$$

Appendix 2: Comparative Static Analysis of a Carbon Tax on Consumption of Fuels and Carbon Emissions

By total differentiating (1) to (3), we can examine the comparative static changes of optimal solutions resulting from changes in carbon tax and land availability. Total

differentiating (1) to (3) and combining $\bar{L} - f - e \geq 0$, we get

$$\begin{pmatrix} \frac{\partial^2 U(m)}{\partial g^2} - c''(g) & \frac{\partial^2 U(m)}{\partial g \partial e} & 0 & 0 \\ \frac{\partial^2 U(m)}{\partial e \partial g} & \frac{\partial^2 U(m)}{\partial e^2} - c''(e) & 0 & -1 \\ 0 & 0 & U_{ff}^* - c''(f) & -1 \\ 0 & 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} dg \\ de \\ df \\ d\lambda \end{pmatrix} = \begin{pmatrix} \delta_g & 0 \\ \delta_e & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} dt \\ d\bar{L} \end{pmatrix}$$

$$H = \begin{pmatrix} \frac{\partial^2 U(m)}{\partial g^2} - c''(g) & \frac{\partial^2 U(m)}{\partial g \partial e} & 0 & 0 \\ \frac{\partial^2 U(m)}{\partial e \partial g} & \frac{\partial^2 U(m)}{\partial e^2} - c''(e) & 0 & -1 \\ 0 & 0 & U_{ff}' - c'(f) & -1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

$$= (\frac{\partial^2 U(m)}{\partial g^2} - c''(g))(U_{ff}' - c'(f)) + (\frac{\partial^2 U(m)}{\partial g^2} - c''(g))(\frac{\partial^2 U(m)}{\partial e^2} - c''(e)) - (\frac{\partial^2 U(m)}{\partial g \partial e})^2$$

where $\frac{\partial U(m)}{\partial e} = U_m' m_e > 0$, $\frac{\partial U(m)}{\partial g} = U_m' m_g > 0$, $\frac{\partial^2 U(m)}{\partial e^2} = U_{mm}'' (m_e)^2 + U_m' m_{ee} < 0$,

$$\frac{\partial^2 U(m)}{\partial g^2} = U_{mm}'' (m_g)^2 + U_m' m_{gg} < 0, \frac{\partial^2 U(m)}{\partial g \partial e} = U_{me}'' m_e m_g + U_m' m_{ge}$$

$$m = r[ag^\rho + (1-a)e^\rho]^{1/\rho}$$

$$m_g = r[ag^\rho + (1-a)e^\rho]^{1/\rho-1} ag^{\rho-1} > 0$$

$$m_e = r[ag^\rho + (1-a)e^\rho]^{1/\rho-1} (1-a)e^{\rho-1} > 0$$

$$m_{gg} = r[ag^\rho + (1-a)e^\rho]^{1/\rho-1} a(\rho-1)g^{\rho-2} + r[ag^\rho + (1-a)e^\rho]^{1/\rho-2} a^2(1-\rho)g^{2(\rho-1)} < 0$$

$$m_{ee} = r[ag^\rho + (1-a)e^\rho]^{1/\rho-1} (1-a)(\rho-1)e^{\rho-2} + r[ag^\rho + (1-a)e^\rho]^{1/\rho-2} (1-a)^2(1-\rho)e^{2(\rho-1)} < 0$$

$$m_{eg} = m_{ge} = r[ag^\rho + (1-a)e^\rho]^{1/\rho-2} a(1-a)(1-\rho)g^{\rho-1}e^{\rho-1} > 0$$

$$m_{gg}m_{ee} - m_{ge}m_{eg} = 0$$

The first term of H is positive according to our assumptions that utility functions are strictly concave and cost functions are convex. After substituting m_g m_e m_{ge} m_{gg} m_{ee} into the last two terms of H function, we get

$$(\frac{\partial^2 U(m)}{\partial g^2} - c''(g))(\frac{\partial^2 U(m)}{\partial e^2} - c''(e)) - (\frac{\partial^2 U(m)}{\partial g \partial e})^2$$

$$= (U_m')^2 (m_{gg}m_{ee} - m_{ge}m_{eg}) + U_{mm}'' U_m' (m_{gg}m_e^2 + m_{ee}m_g^2 - 2m_gm_em_{ge})$$

$$= U_{mm}'' U_m' (m_{gg}m_e^2 + m_{ee}m_g^2 - 2m_gm_em_{ge}) > 0$$

Therefore, the determinant of H is always positive.

$$\frac{dg}{dt} = \frac{1}{H} \begin{pmatrix} \delta_g & \frac{\partial^2 U(m)}{\partial g \partial e} & 0 & 0 \\ \delta_e & \frac{\partial^2 U(m)}{\partial e^2} - c''(e) & 0 & -1 \\ 0 & 0 & U''_{ff} - c''(f) & -1 \\ 0 & 1 & 1 & 0 \end{pmatrix} = \frac{1}{H} \{ \delta_g [U''_{ff} - c''(f) + \frac{\partial^2 U(m)}{\partial e^2} - c''(e)] - \delta_e \frac{\partial^2 U(m)}{\partial g \partial e} \}$$

Since $\delta_g > \delta_e$,

$$\delta_g [U''_{ff} - c''(f) + \frac{\partial^2 U(m)}{\partial e^2} - c''(e)] - \delta_e \frac{\partial^2 U(m)}{\partial g \partial e} < \delta_e [U''_{ff} - c''(f) + \frac{\partial^2 U(m)}{\partial e^2} - c''(e) - \frac{\partial^2 U(m)}{\partial g \partial e}]$$

Then

$$\begin{aligned} \frac{\partial^2 U(m)}{\partial e^2} - \frac{\partial^2 U(m)}{\partial g \partial e} &= U''_{mm}(m_e)^2 + U'_m m_{ee} - U''_{mm} m_e m_g - U'_m m_{ge} \\ &= U''_{mm} ((m_e)^2 - m_e m_g) + U'_m (m_{ee} - m_{ge}) \end{aligned}$$

Demand for fuels can be derived through the following problem:

$$\min_{e,g} p_e e + p_g g \quad \text{s.t.} \quad m = r[ag^\rho + (1-a)e^\rho]^{1/\rho}$$

Where p_e and p_g are fuel prices. Solving the first order conditions gives

$$\frac{p_e}{p_g} = \frac{c'(e)}{c'(g)} = \frac{m_e}{m_g}$$

and the demand functions for fuels are

$$g = \frac{M/\gamma}{(a + (1-a)(\frac{ac'(e)}{(1-a)c'(g)})^{\frac{\rho}{\rho-1}})^{1/\rho}} \quad \text{and} \quad e = \frac{M/\gamma}{((1-a) + a(\frac{ac'(e)}{(1-a)c'(g)})^{\frac{\rho}{\rho-1}})^{1/\rho}}, \quad \text{respectively.}$$

Since e is more costly to be produced than g according to our assumption, $c'(e) > c'(g)$,

we have $m_e > m_g$. Combining $m_{ee} - m_{ge} < 0$, it is straightforward to obtain

$$\frac{\partial^2 U(m)}{\partial e^2} - \frac{\partial^2 U(m)}{\partial g \partial e} < 0 \quad \text{and} \quad \frac{dg}{dt} < 0. \quad (\text{A2.1})$$

$$\frac{de}{dt} = \frac{1}{H} \begin{pmatrix} \frac{\partial^2 U(m)}{\partial g^2} - c''(g) & \delta_g & 0 & 0 \\ \frac{\partial^2 U(m)}{\partial e \partial g} & \delta_e & 0 & -1 \\ 0 & 0 & U''_{ff} - c''(f) & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix} = \frac{1}{H} \{ \delta_e [\frac{\partial^2 U(m)}{\partial g^2} - c''(g)] - \delta_g \frac{\partial^2 U(m)}{\partial e \partial g} \}$$

Where

$$\begin{aligned} \delta_e [\frac{\partial^2 U(m)}{\partial g^2} - c''(g)] - \delta_g \frac{\partial^2 U(m)}{\partial e \partial g} &= \delta_e [U''_{mm} m_g^2 + U'_m m_{gg} - c''(g)] - \delta_g (U''_{mm} m_e m_g + U'_m m_{ge}) \\ &= U''_{mm} (\delta_e m_g^2 - \delta_g m_e m_g) + U'_m (\delta_e m_{gg} - \delta_g m_{ge}) - \delta_e c''(g) \\ &= \frac{dp(m)}{dm} m_g (\delta_e m_g - \delta_g m_e) + p(m) (\delta_e m_{gg} - \delta_g m_{ge}) - \frac{\delta_e dc'(g)}{dg} \\ &= \frac{p(m) (\delta_e m_g - \delta_g m_e)}{g} \frac{1}{\varepsilon_m} E_{mg} + p(m) (\delta_e m_{gg} - \delta_g m_{ge}) - \frac{\delta_e c'(g)}{s_g g} \\ &= \frac{p(m) (\delta_e m_g - \delta_g m_e)}{g} \left(\frac{E_{mg}}{\varepsilon_m} + \frac{d(\delta_e m_g - \delta_g m_e)}{dg} * \frac{g}{(\delta_e m_g - \delta_g m_e)} \right) - \frac{\delta_e c'(g)}{s_g g} \quad (\text{A2.2}) \\ &= \frac{p(m) (\delta_e m_g - \delta_g m_e)}{g} \left(\frac{E_{mg}}{\varepsilon_m} + \varepsilon_{\delta_g m_e - \delta_e m_g} \right) - \frac{\delta_e c'(g)}{s_g g} \end{aligned}$$

Where $p(m)$ is the price of miles, which depends upon the marginal costs of fuels; ε_m , E_{mg} , s_g are the demand elasticity of miles, output elasticity of miles with respect to gasoline and gasoline supply elasticity, respectively. Here, we define m_g and m_e as fuel efficiency to measure the marginal contribution of fuels in producing miles. For instance, an increase in g leads to a decrease in m_g and an increase in m_e . $\varepsilon_{\delta_g m_e - \delta_e m_g}$ measures the elasticity in the difference of fuel efficiency due to the change in g .

$$\text{It is straightforward to show } \frac{df}{dt} = -\frac{de}{dt}, \quad (\text{A2.3})$$

$$\text{and } \frac{d\lambda}{dt} = (c''(f) - U''_{ff}) \frac{de}{dt} \quad (\text{A2.4})$$

$$\frac{dg}{dL} = \frac{1}{H} \begin{pmatrix} 0 & \frac{\partial^2 U(m)}{\partial g \partial e} & 0 & 0 \\ 0 & \frac{\partial^2 U(m)}{\partial e^2} - c''(e) & 0 & -1 \\ 0 & 0 & U_{ff}'' - c''(f) & -1 \\ 1 & 1 & 1 & 0 \end{pmatrix} = \frac{-1}{H} \frac{\partial^2 U(m)}{\partial g \partial e} (U_{ff}'' - c''(f)) \quad (\text{A2.5})$$

$$\frac{dg}{dL} < 0 \Leftrightarrow \frac{\partial^2 U(m)}{\partial g \partial e} < 0 \Leftrightarrow \frac{\sigma}{\varepsilon_m} + 1 < 0 \Leftrightarrow \varepsilon_m > -\sigma_m, \text{ where } \sigma_m \text{ is the elasticity of}$$

substitution between g and e .

$$\frac{de}{dL} = \frac{1}{H} \begin{pmatrix} \frac{\partial^2 U(m)}{\partial g^2} - c''(g) & 0 & 0 & 0 \\ \frac{\partial^2 U(m)}{\partial e \partial g} & 0 & 0 & -1 \\ 0 & 0 & U_{ff}'' - c''(f) & -1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

$$= \frac{1}{H} (U_{ff}''(f) - c''(f)) \left(\frac{\partial^2 U(m)}{\partial g^2} - c''(g) \right) > 0 \quad (\text{A2.6})$$

$$\frac{df}{dL} = \frac{1}{H} \begin{pmatrix} \frac{\partial^2 U(m)}{\partial g^2} - c''(g) & \frac{\partial^2 U(m)}{\partial g \partial e} & 0 & 0 \\ \frac{\partial^2 U(m)}{\partial e \partial g} & \frac{\partial^2 U(m)}{\partial e^2} - c''(e) & 0 & -1 \\ 0 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \end{pmatrix}$$

$$= \frac{1}{H} \left[\left(\frac{\partial^2 U(m)}{\partial g^2} - c''(g) \right) \left(\frac{\partial^2 U(m)}{\partial e^2} - c''(e) \right) - \left(\frac{\partial^2 U(m)}{\partial g \partial e} \right)^2 \right] > 0 \quad (\text{A2.7})$$

$$\frac{d\lambda}{dL} = \frac{1}{H} \begin{pmatrix} \frac{\partial^2 U(m)}{\partial g^2} - c''(g) & \frac{\partial^2 U(m)}{\partial g \partial e} & 0 & 0 \\ \frac{\partial^2 U(m)}{\partial e \partial g} & \frac{\partial^2 U(m)}{\partial e^2} - c''(e) & 0 & 0 \\ 0 & 0 & U_{ff}'' - c''(f) & 0 \\ 0 & 1 & 1 & 1 \end{pmatrix}$$

$$= \frac{U''_{ff} - c''(f)}{H} \frac{df}{dL} < 0 \quad (\text{A2.8})$$

Appendix 3: Proof of the Change of Total GHG Emissions

$$\begin{aligned} \frac{dGHG}{dt} &= \delta_g \frac{dg}{dt} + \delta_e \frac{de}{dt} \\ &= \delta_g \frac{1}{H} \left\{ \delta_g [U''_{ff} - c''(f)] + \frac{\partial^2 U(m)}{\partial e^2} - c''(e) \right\} - \delta_e \frac{\partial^2 U(m)}{\partial g \partial e} + \delta_e \frac{1}{H} \left\{ \delta_e \left[\frac{\partial^2 U(m)}{\partial g^2} - c''(g) \right] - \delta_g \frac{\partial^2 U(m)}{\partial e \partial g} \right\} \\ &= \frac{1}{H} \left\{ \delta_g^2 [U''_{ff} - c''(f)] + U''_{mm} m_e^2 + U'_m m_{ee} - c''(e) \right\} + \delta_e^2 [U''_{mm} m_g^2 + U'_m m_{gg} - c''(g)] - 2\delta_e \delta_g (U''_{me} m_e m_g + U'_m m_{ge}) \} \\ &= \frac{1}{H} \left\{ \delta_g^2 [U''_{ff} - c''(f)] - c''(e) - \delta_e^2 c''(g) + U''_{mm} (\delta_g m_e - \delta_e m_g)^2 + U'_m (\delta_g^2 m_{ee} + \delta_e^2 m_{gg} - 2\delta_e \delta_g m_{ge}) \right\} < 0 \quad (\text{A3}) \end{aligned}$$

Appendix 4: Comparative Static Analysis of a Blend Mandate and a Biofuel Tax

Credit

The maximization problem (P) reduces to

$$\text{Max}_{g,e,f} U(m(g,e)) + U(f) - c(g) - c(e) - c(f) + se$$

$$\text{subject to } m(g,e) = \gamma [a g^\rho + (1-a) e^\rho]^{1/\rho}$$

$$e = \frac{\beta}{1-\beta} g, \quad \bar{L} - f - e \geq 0$$

The ratio of ethanol to gasoline is $e/g = \beta/(1-\beta)$. For the ease of exposition, if let $\omega = 1/\beta - 1$,

then $g = \omega e$. Then the production function of miles reduces to

$$m = r[a\omega^\rho + (1-a)]^{1/\rho} e = A(\omega)e$$

The first order conditions for (P1) are:

$$\frac{\partial U(m)}{\partial e} - c'(e) - \omega c'(\omega e) + s - \lambda = 0$$

$$\frac{\partial U(f)}{\partial f} - c'(f) - \lambda = 0$$

Total differentiating above equations with $\bar{L} - f - e \geq 0$, we get

$$\begin{pmatrix} \frac{\partial^2 U(m)}{\partial e^2} - \omega^2 c''(\omega e) - c''(e) & 0 & -1 \\ 0 & U_{ff}'' - c''(f) & -1 \\ 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} de \\ df \\ d\lambda \end{pmatrix} = \begin{pmatrix} B & 0 & -1 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} d\omega \\ d\bar{L} \\ ds \end{pmatrix}$$

where $B = c'(\omega e) + \omega e c''(\omega e) - (U_{mm}'' m + U_m')$. $A'(\omega)$

$$\begin{aligned} &= c'(g) + g c''(g) - \left(\frac{dP(m)}{dm} m + P(m) \right) A'(\omega) \\ &= c'(g) \left(1 + \frac{1}{s_g} \right) - A'(\omega) P(m) \left(1 + \frac{1}{\varepsilon_m} \right) \end{aligned}$$

Therefore, when the demand for miles is inelastic, $B > 0$.

$$H = \begin{pmatrix} \frac{\partial^2 U(m)}{\partial e^2} - \omega^2 c''(\omega e) - c''(e) & 0 & -1 \\ 0 & U_{ff}'' - c''(f) & -1 \\ 1 & 1 & 0 \end{pmatrix} = \frac{\partial^2 U(m)}{\partial e^2} - \omega^2 c''(\omega e) - c''(e) + U_{ff}'' - c''(f) < 0$$

$$\frac{de}{d\beta} = -\frac{1}{(\omega+1)^2} \frac{de}{d\omega} = -\frac{1}{(\omega+1)^2} \frac{1}{H} \begin{pmatrix} c'(\omega e) + \omega e c''(\omega e) & 0 & -1 \\ 0 & U_{ff}'' - c''(f) & -1 \\ 0 & 1 & 0 \end{pmatrix} = -\frac{1}{(\omega+1)^2} \frac{B}{H} \quad (\text{A4.1})$$

$$\frac{dg}{d\beta} = -\frac{1}{(\omega+1)^2} \frac{d(\omega e)}{d\omega} = -\frac{1}{(\omega+1)^2} \left(e + \omega \frac{B}{H} \right) \quad (\text{A4.2})$$

$$\frac{df}{d\beta} = -\frac{1}{(\omega+1)^2} \frac{df}{d\omega} = \frac{1}{(\omega+1)^2} \frac{B}{H} \quad (\text{A4.3})$$

$$\frac{d\lambda}{d\beta} = -\frac{1}{(\omega+1)^2} \frac{d\lambda}{d\omega} = \frac{1}{(\omega+1)^2} \frac{B}{H} (U_{ff}'' - c''(f)) \quad (\text{A4.4})$$

$$\frac{de}{ds} = \frac{1}{H} \begin{pmatrix} -1 & 0 & -1 \\ 0 & U_{ff}'' - c''(f) & -1 \\ 0 & 1 & 0 \end{pmatrix} = \frac{-1}{H} > 0 \quad (\text{A4.5})$$

$$\frac{dg}{ds} = \frac{d(\omega e)}{ds} = \omega \frac{de}{ds} > 0 \quad (\text{A4.6})$$

$$\frac{df}{ds} = \frac{1}{H} \begin{pmatrix} \frac{\partial^2 U(m)}{\partial e^2} - \omega^2 \dot{c}(\omega e) - \dot{c}(e) & -1 & -1 \\ 0 & 0 & -1 \\ 1 & 0 & 0 \end{pmatrix} = \frac{1}{H} < 0 \quad (\text{A4.7})$$

$$\frac{d\lambda}{ds} = \frac{1}{H} \begin{pmatrix} \frac{\partial^2 U(m)}{\partial e^2} - \omega^2 \dot{c}(\omega e) - \dot{c}(e) & 0 & -1 \\ 0 & U''_{ff} - c''(f) & 0 \\ 1 & 1 & 0 \end{pmatrix} = \frac{1}{H} (U''_{ff} - c''(f)) > 0 \quad (\text{A4.8})$$

Further, we examine the second derivatives of variables with respect to the blend mandate and the subsidy.

$$\frac{d^2 e}{d\beta ds} > 0, \frac{d^2 g}{d\beta ds} < 0, \frac{d^2 f}{d\beta ds} < 0 \text{ and } \frac{d^2 \lambda}{d\beta ds} > 0.$$

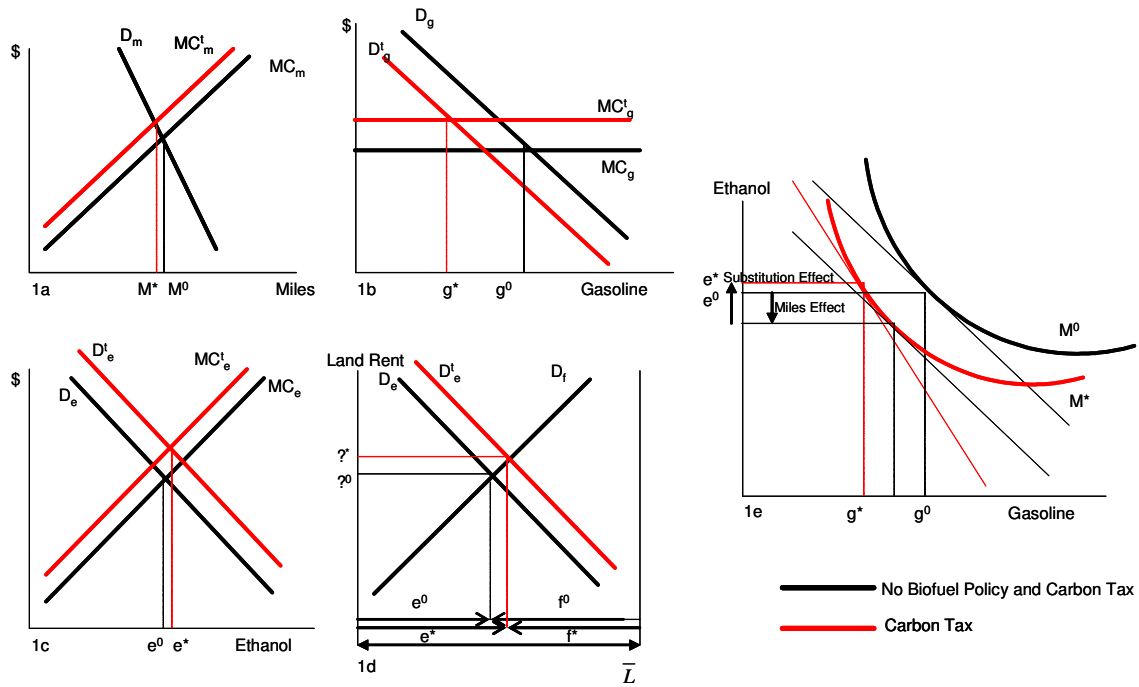


Figure 1: Carbon Tax Increases Ethanol Consumption

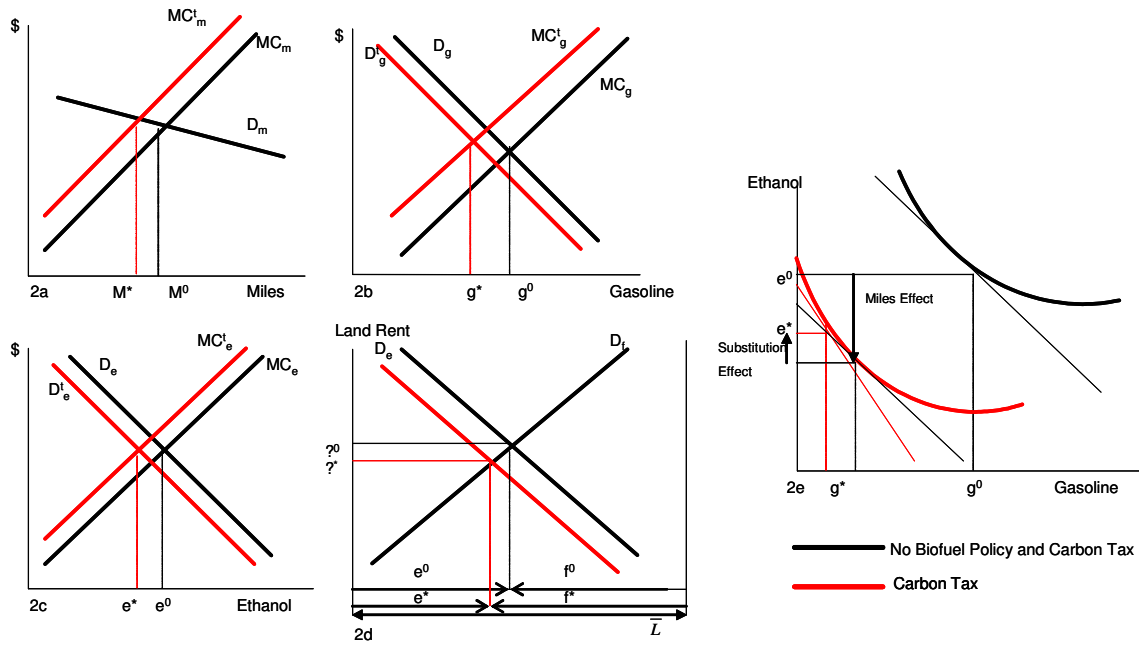


Figure 2: Carbon Tax Decreases Ethanol Consumption

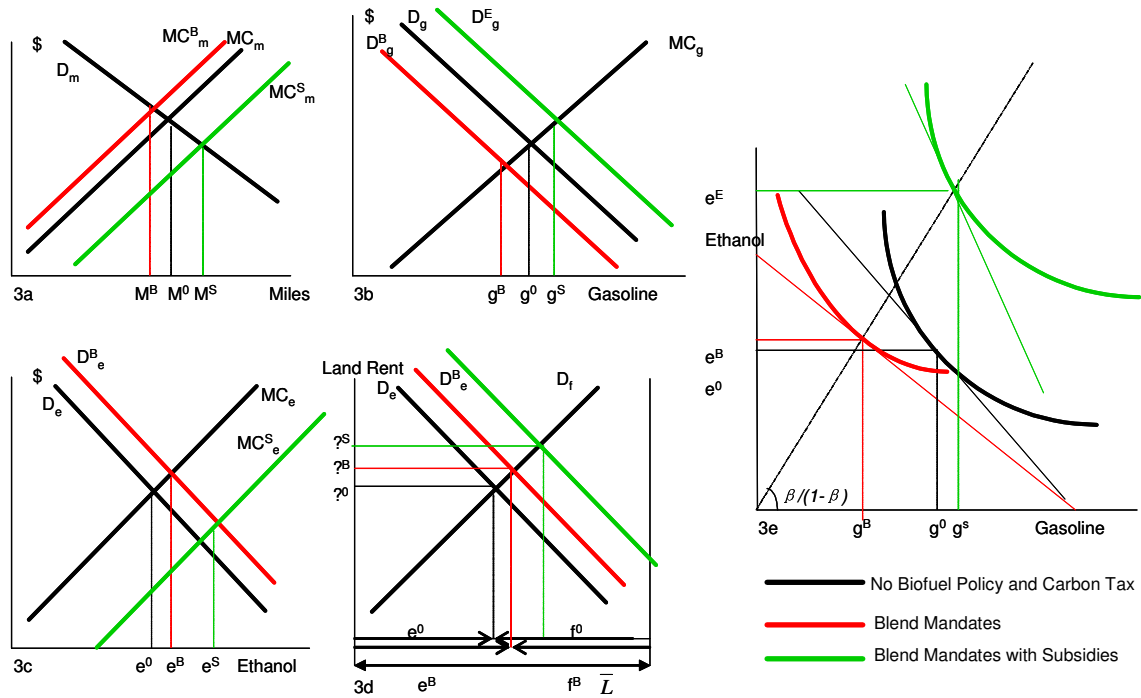


Figure 3: Impacts of Ethanol Mandates and Subsidies when Miles Demand is Inelastic

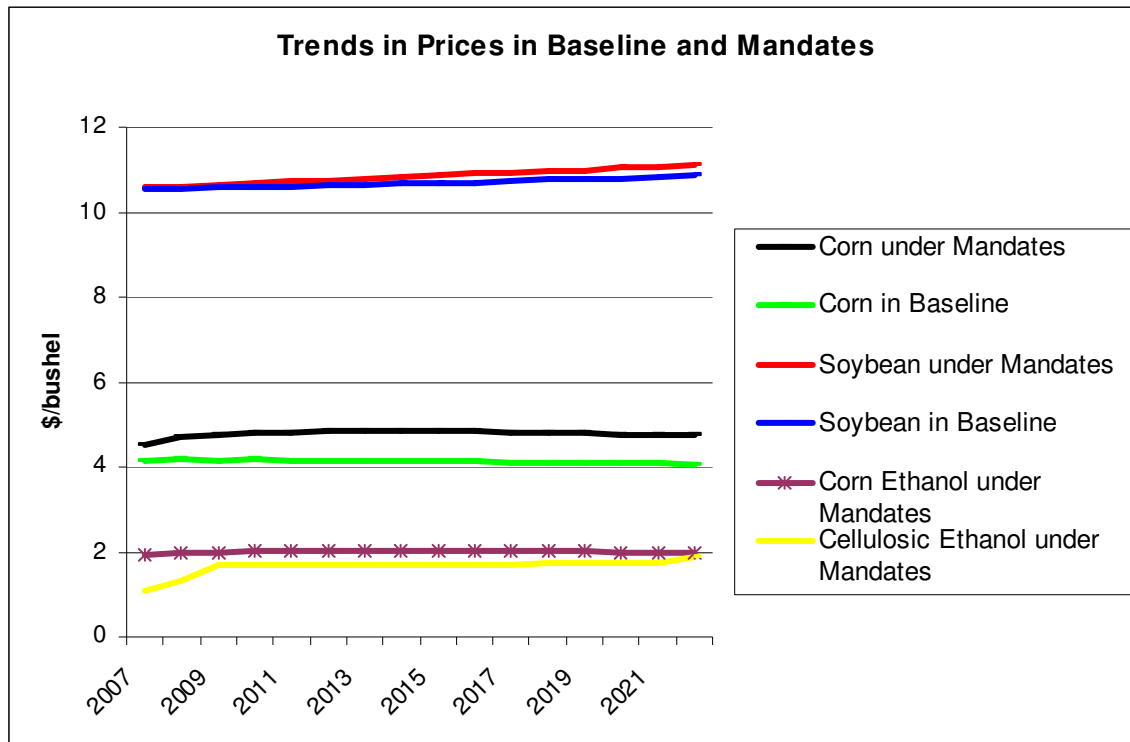


Figure 4: Trends in Crop Price Changes

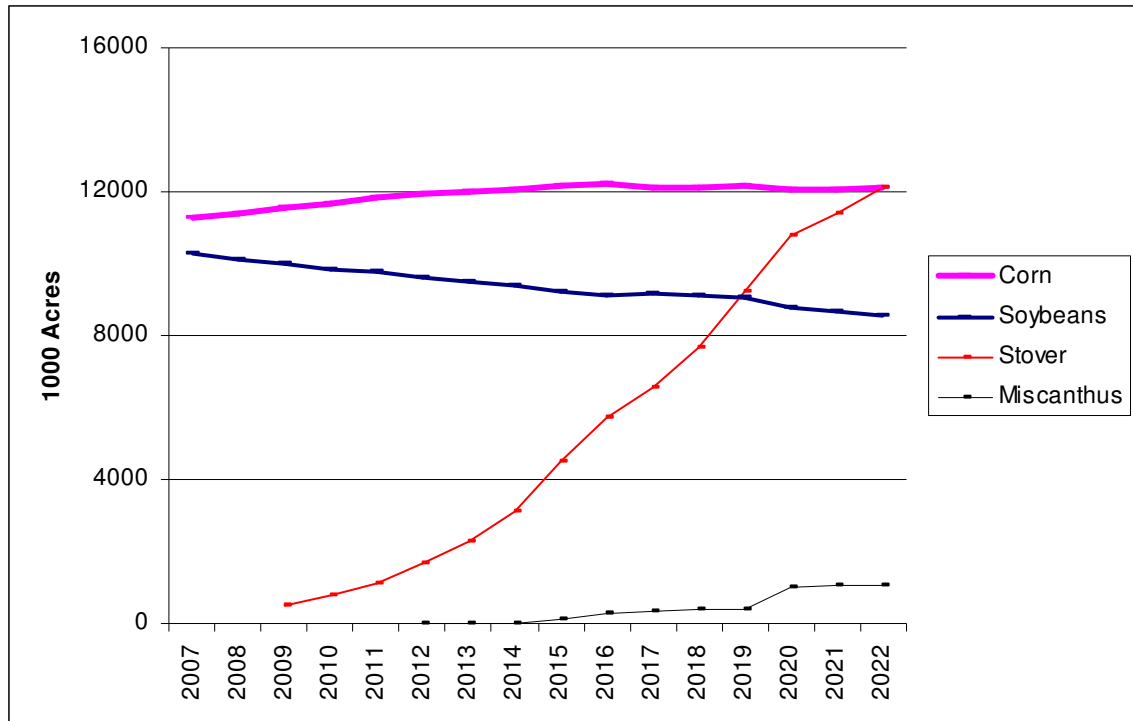
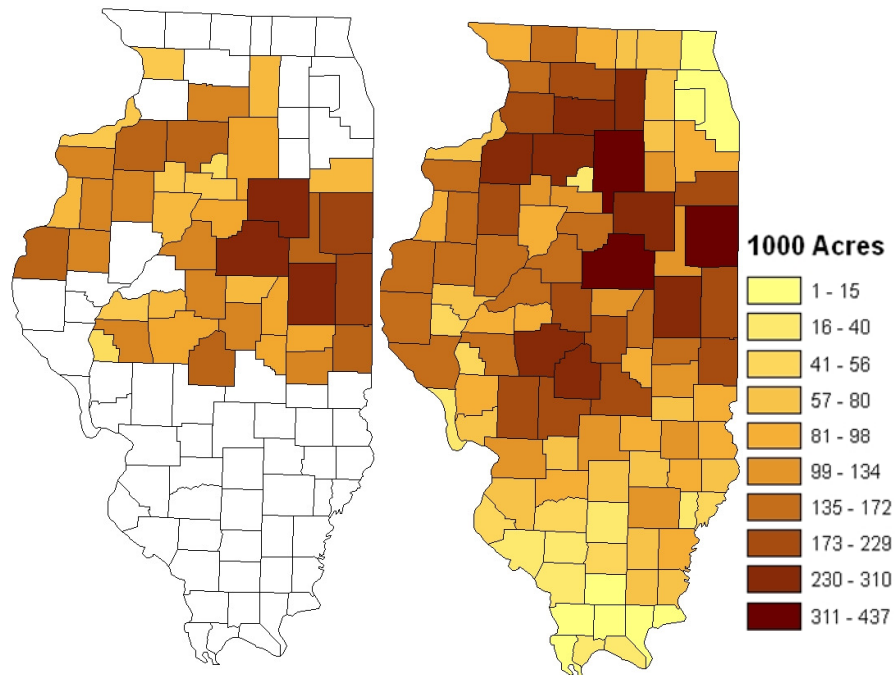


Figure 5: Trends in Acreages

Corn Stover Acres in 2015 and 2022



Miscanthus Acres in 2015 and 2022

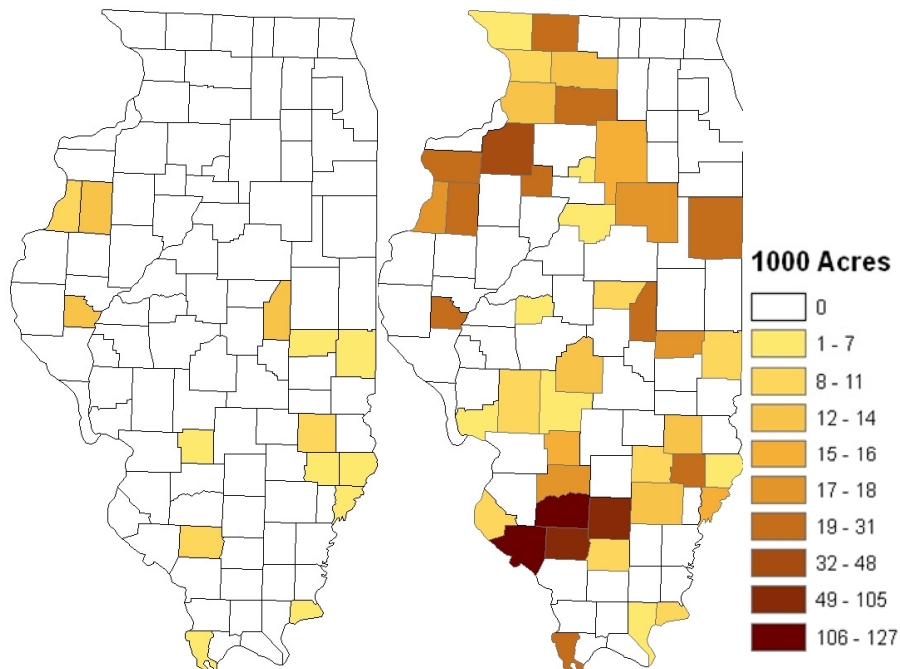


Figure 6: Spatial Distribution in Land Use with Biofuel Blending Mandates