A DYNAMIC ANALYSIS OF U.S. BIOFUELS POLICY IMPACT ON LAND USE, GREENHOUSE GAS EMISSIONS AND SOCIAL WELFARE

BY

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DISSERTATION

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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 dissertation presents a framework to examine the extent to which biofuel policies reduce gasoline consumption and GHG emissions and their implications for land allocation among food and fuel crops, food and fuel prices and social welfare. It first develops a stylized model of the food and fuel sectors linked by a limited land availability to produce food and fuel crops. It then analyzes the mechanisms through which biofuel mandates and subsidies affect consumer choices and differ from a carbon tax policy. A dynamic, multi-market equilibrium model, Biofuel and Environmental Policy Analysis Model (BEPAM), is developed to estimate the welfare costs of these policies and to explore the mix of biofuels from corn and various cellulosic feedstocks that are economically viable over the 2007-2022 period under alternative policies. It distinguishes biofuels produced from corn and several cellulosic feedstocks including crop residues (corn stover and wheat straw) and bioenergy crops (miscanthus and switchgrass). A crop productivity model MISCANMOD is used to simulate the yields of miscanthus and switchgrass. The biofuel policies considered here include the biofuel mandate under the Renewable Fuel Standard (RFS), various biofuel subsidies and import tariffs. The effects of these policies are compared to those of a carbon tax policy that is directly targeted to reduce GHG emissions.

The stylized model shows that a carbon tax can reduce gasoline consumption and lower GHG emissions, and is likely to increase biofuel consumption with a higher elasticity of substitution between gasoline and biofuels and an elastic supply of gasoline. A biofuel mandate would reduce gasoline consumption, but the effects on GHG emissions depend on parameters in the fuel sector, such as the demand elasticity of miles, the elasticity of substitution between

gasoline and biofuels and the supply elasticity of gasoline. A biofuel mandate accompanied with subsidies would create incentives to increase the consumption of the blended fuel by lowering its price. Gasoline consumption and GHG emissions would increase under the mandate and subsidy relative to a mandate alone.

The numerical simulation is used to analyze the impacts of biofuel mandate and subsidies relative to a carbon tax. We find a biofuel mandate alone leads to a welfare gain of 0.1% while reducing GHG emissions by 1% relative to a carbon tax of $30 per ton of CO_2e (Carbon dioxide equivalent). However, it would increase corn and soybean prices in 2022 by 19% and 20% relative to the carbon tax. The provision of biofuel subsidies that accompany the mandate under the RFS significantly changes the mix of bofuels in favor of cellulosic biofuels produced from high yielding perennial grasses and reduces the adverse impact of RFS alone on food prices. Biofuel mandates and subsidies also reduce GHG emissions by 3% relative to the carbon tax but at a welfare cost of $106 B relative to the tax. To meet the cellulosic biofuel mandates, a mix of feedstocks (corn stover, wheat straw, switchgrass and miscanthus) is used, where the mix differs over time, with biofuels from miscanthus meeting about 90% of the cellulosic ethanol produced between 2007- 2022. Corn stover comes primarily from the plain states while wheat straw is collected mainly in the central and northern plains and western mountain states. Production of miscanthus is more concentrated in the Great Plains and in the Midwest and along lower reaches of the Mississippi river. Switchgrass, though not as competitive as miscanthus in terms of yields and costs of production in most parts of the country, is still produced in a significant amount in northern and central Texas and Wisconsin where miscanthus yields are relatively low.

We then analyze the implications of imposing import tariffs on biofuels for social welfare and GHG emissions in an open economy considering trade in biofuels. When biofuel mandates

and subsidies are in place, the imposition of import tariffs would significantly reduce the imports of sugarcane ethanol by 28% relative to biofuel mandates and subsidies. It also results in a higher GHG intensity of the blended fuel and marginally increases GHG emissions but raises social welfare by 0.01% relative to biofuel mandates and subsidies.

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Chapter 1: Introduction

1.1 Motivation

Concerns about energy independence, high gasoline prices and greenhouse gas (GHG) 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. sought to promote the production and use of first-generation biofuel produced from corn. This has changed due to the concerns about the implications of the expansion in corn ethanol production for food/feed prices and exports (reviewed in Runge and Senauer 2007) and the skepticism about the potential of corn ethanol to reduce GHG emissions (Fargione et al. 2008; Searchinger et al. 2008). This has led to farm policy and energy policy shifting the focus from corn ethanol to non-grain based or second-generation cellulosic biofuels.

Cellulosic biofuels can be produced from several different feedstocks such as crop residues, perennial grasses (or dedicated energy crops) and woody biomass. Cellulosic biofuels are potentially more productive in their use of land and have lower GHG intensity per liter than corn ethanol (Khanna 2008). A commercial technology to produce cellulosic biofuels is yet to be developed. To promote their production, the Energy Independence and Security Act (EISA) of 2007 imposes a Renewable Fuels Standard (RFS) that sets annual targets for blending biofuels with gasoline over the 2007-2022 period with a substantial portion of these to be met by 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 biofuels with gasoline.

To meet the increased demand for biofuels, the U.S. also has the option of importing ethanol from Brazil, a major producer of sugarcane ethanol. Sugarcane ethanol can reduce GHG emissions by 70% relative to gasoline (Lasco and Khanna 2009; Macedo, Seabra and Silva 2008; Von Lampe 2006), and qualifies as an advanced biofuel. It also can compete with corn ethanol to meet the RFS mandate under the category of conventional biofuels. Moreover, sugarcane ethanol from Brazil is cheaper than cellulosic ethanol and under certain market conditions even cheaper than corn ethanol (Lasco et al. 2009). However, to protect domestic biofuel industry import tariffs are imposed by the U.S. to restrict ethanol imports from Brazil.

Economic theory suggests that the least cost approach to meeting desired GHG reduction goals is by pricing carbon at its marginal social damage, because a carbon tax can adjust prices of fuels to reflect their carbon intensities. Biofuel mandates are expected to lower GHG intensities of the blended fuel per liter by displacing gasoline, but the effect on overall GHG emissions is uncertain. It will depend on the effect of the mandates on the price of the blended fuel and the response of fuel consumers to that price. That in turn depends on the costs of producing biofuels and gasoline prices. The impact of the mandates on gasoline prices will depend on gasoline prices responding to lower demand of gasoline and the substitutability between gasoline and biofuels. A mandate accompanied by biofuel subsidies will lower fuel prices and create incentives for consumers to increase the consumption of the blend fuel relative to a mandate alone. That offsets, at least in part, the benefits of the mandate in lowering GHG intensity of the blend fuel. In the presence of the biofuel mandates and subsidies, import tariffs are likely to distort not only the mix of biofuels consumed depending on the competitiveness of alternative biofuels, but also affect the GHG mitigation benefits of displacing gasoline using biofuels.

Moreover, biofuel policies can be expected to impact food consumers by diverting land from food to fuel production and affecting food/feed production and prices. The impact on food prices can be mitigated not only by productivity enhancement in food crops, but also by using crop residues, high-yielding bioenergy crops and ethanol imports to meet the mandates. The extent to which marginal lands can be used to produce food crops and bioenergy crops also has important implications for food/feed production and prices.

1.2 Research Objectives

The purpose of this dissertation is to assess the economic and environmental effects of biofuel policies on the agricultural and fuel sectors. It first analyzes the effects of biofuel policies on cropland allocation among food and fuel crops spatially and temporally. It then examines the impacts of biofuel policies on crop and livestock production, food prices, vehicle miles travelled, fuel prices, and commodity trade with the rest of the world, and compares the implications for GHG emissions and social welfare with a carbon tax policy. It also examines the economically viable mix of cellulosic feedstocks spatially and temporally under alternative policy scenarios. Biofuel policies considered in this dissertation include RFS mandates, volumetric subsidies and import tariffs.

1.3 Research Methods

This dissertation first develops a stylized framework of the food and fuel sectors linked by the limited land availability to produce food and fuel crops and analyzes the mechanisms through which biofuel mandates and subsidies affect consumer choices and differ from a carbon tax policy. It then operationalizes this framework by developing a dynamic, multi-market equilibrium model, Biofuel and Environmental Policy Analysis Model (BEPAM) to analyze the markets for fuel, biofuel, food/feed crops and livestock for the period 2007-2022.

BEPAM considers not only biofuels produced from corn and several cellulosic feedstocks but also biofuel imports from Brazil and Caribbean countries. Cellulosic feedstocks considered here include crop residues (corn stover and wheat straw) and bioenergy crops (switchgrass and miscanthus). In the absence of long term observed yields for miscanthus and switchgrass, BEPAM uses a crop productivity model MISCANMOD developed by Jain et al. (2010) to simulate the yields of miscanthus and switchgrass. BEPAM treats each Crop Reporting District (CRD) as a decision making unit where crop yields, costs of crop and livestock production, land availability and GHG emissions differ across CRDs. Thus, it can determine the allocation of cropland to food crops and fuel crops spatially and temporally as well as the economically viable mix of corn and cellulosic feedstocks under alternative climate and biofuel policies. BEPAM also distinguishes gasoline supply from domestic production and the rest of the world to capture the effect of biofuel policies on the world price of gasoline. 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.

1.4 Key Contributions

The stylized model developed here contributes to the existing literature analyzing the economic impacts of biofuel policies in several aspects. It assumes gasoline and biofuels as imperfect substitutes in producing the blended fuel, unlike existing studies either assuming the two fuels as complements (Elobeid and Tokgoz 2008; Vedenov and Wetzstein 2008) or perfect substitutes (such as de Gorter and Just 2009; de Gorter and Just 2010). The assumption of perfect substitutability between gasoline and biofuels holds only if the fuel markets are not constrained by the fleet structure and the available ethanol distribution network and infrastructure for retail ethanol sales. To accommodate with the prevailing market conditions in the U.S, we model gasoline and biofuels as imperfect substitutes at aggregate level, and consider the implications of alternative substitutability between the two fuels for the fuel and food consumption. We consider externality costs caused by GHG emissions from fuel consumption and compare social welfare and GHG emissions of biofuel policies relative to a carbon tax. Many studies in the existing literature do not consider environmental effects of biofuel policy (de Gorter and Just 2009; de Gorter and Just 2010; Elobeid and Tokgoz 2008; Gardner 2007). We analyze the mechanisms that biofuel policies affect the consumption of fuels and how they differ from a carbon tax. In addition, the framework developed here uses a limited availability of cropland to link agricultural and fuel sectors, and can be used to analyze the effect of biofuel policy on food prices and land rent.

The numerical land use model developed in this study differs from the existing simulation models in the literature. It considers gasoline supply from domestic production and the rest of world to capture the effect of biofuel policy on the world gasoline price. It allows 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, this study uses the estimated own and cross price crop elasticities to limit the flexibility of crop acreage changes (Huang and Khanna 2010). It also quantifies 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.

1.5 Key Findings

We first analyze the impacts of biofuel mandate and subsidies relative to a carbon tax. We find that a tax of \$30 per ton of CO_2e (Carbon dioxide equivalent) would induce additional production of corn ethanol and reduce the consumption of gasoline by 3-4% depending on market conditions in the fuel sector, but would not create incentives for the production of cellulosic ethanol. The tax would reduce GHG emissions by 3-4% compared to a business as usual (BAU) scenario, and increase the present value of domestic social welfare by 0.7-1.6%. The upper end of these ranges would be achieved with a higher demand elasticity of miles.

A biofuel mandate (without any subsidies) would use corn ethanol to the maximum level allowed while bioenergy crops would meet 90% of the advanced biofuel targets with crop residues meeting the rest. The mandate would result in a reduction in gasoline consumption by 5-8% while about 88% of the reduction would be from foreign producers. GHG emissions under a mandate alone decrease by 3-5% relative to the BAU. The reduction in externality costs due to GHG emissions and the partial shift in burden of the mandate to foreign gasoline producers results in a gain in domestic social welfare as compared to the BAU and even compared to the carbon tax policy. We also find the existing subsidies for cellulosic biofuels significantly shift the mix of biofuels such that 87% of the cumulative biofuels over the 2007-2022 would be produced from cellulosic feedstocks. The changes in the mix of biofuels in favor of the low carbon intensity cellulosic biofuels lead to a greater reduction in GHG emissions (5-9%) than under the mandate alone and larger than under the carbon tax. Domestic social welfare under the biofuel mandate and subsidies is higher than the BAU but 1% lower than under the carbon tax scenario. The upper end of above ranges under a mandate and a mandate with subsidies would be achieved with a high elasticity of substitution between gasoline and ethanol.

Corn price under the carbon tax policy would increase by 7-12% relative to the BAU depending on parameters in the fuel sector. Similarly, a biofuel mandate alone would lead to an increase in corn price by 23-34% due to increasing demand for corn ethanol. A biofuel mandate and subsidy would mitigate the competition for land and reduce food prices by 10-14% relative to the BAU through changing the mix of biofuels in favor of cellulosic biofuels.

To meet the cellulosic biofuel mandates, a mix of feedstocks (corn stover, wheat straw, switchgrass and miscanthus) is used, where the mix differs over time. The production of energy crops increases over time with miscanthus playing a more important role in meeting the cellulosic biofuel target, accounting for 91% and 90% of the total cellulosic ethanol produced between 2007- 2022 under the mandate and the mandate and subsidy scenarios, respectively. Corn stover comes primarily from the plain states Nebraska, South Dakotas and Kansas. Wheat straw is collected mainly in the central and northern plains and western mountain states (Kansas, Nebraska, North and South Dakotas, Montana, Idaho and Washington). Production of miscanthus is more concentrated in the Great Plains (South Dakota, Nebraska, Kansas and Oklahoma), and in the Midwest and along lower reaches of the Mississippi river. Switchgrass, though not as competitive as miscanthus in terms of yields and costs of production in most parts of the country, is still produced in a significant amount in northern and central Texas and Wisconsin where miscanthus yields are relatively low.

We then analyze the implications of incorporating trade in biofuels for social welfare and GHG emissions by considering trade in biofuels. We find that a binding biofuel mandate would rely on corn ethanol to meet about 64% of cumulative biofuel mandate over the 2007-2022 period while sugarcane ethanol imports would meet about 5-7% of the mandate. Miscanthus is the primary feedstock in meeting 58-75% of the advanced biofuel target. A higher growth rate of sugarcane ethanol production achieves the upper end of above ranges. The biofuel mandate also results in a reduction in cumulative gasoline consumption over the period of 2007-2022 by about 7% relative to BAU. Reduced GHG intensity of the blended fuel reduces cumulative GHG emissions by about 1.1 B metric tons (4% relative to BAU) while social welfare is 0.9% higher than the BAU. Corn and soybean prices in 2022 are 24-29% and 21-26% higher than under the BAU despite the gains in crop productivity.

The provision of tax credits for biofuels would change the mix of biofuels in favor of cellulosic ethanol, and reduce sugarcane ethanol imports by 2-4% over the 2007-2022 period relative to the BAU. The total GHG emissions would now be decreased by about 5% relative to the BAU scenario over the 2007- 2022 period. Domestic social welfare is higher than the BAU but 0.3% lower than the mandate alone due to a large government expenditure on biofuel subsidies. Corn price in 2022 is 10-14% lower relative to the BAU. The imposition of import tariffs would significantly reduce the imports of sugarcane ethanol by 28-46% relative to the BAU. It also results in a higher GHG intensity of the blended fuel and increases GHG emissions but raises social welfare by 0.3% relative to the BAU.

1.6 Outline

The rest of the dissertation is organized as follows. Chapter 2 reviews the existing literature on effects of biofuel and climate policies on food/feed prices and land use, and briefly describes current biofuel legislations whose effects are being analyzed in this study. It also lays out key contributions of this study to the existing literature. Chapter 3 presents a stylized framework to analyze food and fuel consumption decisions in the presence of biofuels and various biofuel policies. Chapter 4 describes the simulation model. Data and parameters used for the simulation model are described in Chapter 5. In Chapter 6, we first examine the impacts of the biofuel mandates and subsidies, and compare biofuel policies to those under a carbon tax policy. Then we expand the framework in chapter 7 to consider trade in biofuels and examine the implications of trade liberalization in biofuel markets for social welfare and GHG emissions. Chapter 8 summarizes the results and draws conclusions.

Chapter 2: Review of Biofuel Policy and Related Literature

This chapter includes three sections. Section 1 describes recent legislation of biofuels, including the RFS mandates, volumetric tax credits for blending gasoline and ethanol, import tariffs and proposed climate change legislation. Section 2 reviews the literature on economics of biofuel and climate policies while section 3 describes the contribution of this dissertation to the existing literature.

2.1 Policy Background

The EISA established the RFS in 2007 to require a minimum volume of renewable fuel to be used each year in the transportation sector with the goals of 136 B liters of biofuel production in 2022. It specifies five separate categories of biofuels, including renewable fuel, conventional biofuels, advanced biofuel, cellulosic biofuel, and biomass-based diesel. It also requires each of these categories of biofuels to achieve certain minimum thresholds of lifecycle GHG emission performance relative to the lifecycle GHG emissions of the 2005 baseline average gasoline. Lifecycle GHG emissions include direct emissions from all stages of fuel and feedstock production, delivery of feedstock to refinery, conversion from biomass to biofuels and distribution and use of the finished fuel to the ultimate consumers. It also includes indirect emissions from land use changes (EISA 2007).

The goal of the RFS mandate is to produce renewable fuel using renewable biomass to reduce the quantity of fossil fuel used in the transportation sector. Renewable biomass here is defined to include each of following feedstocks: (i) Planted crops and crop residues from cleared or cultivated agricultural land before the enactment of EISA; (ii) Woody biomass; (iii) Animal wastes and animal byproducts and (iv) Algae (EISA 2007). Total requirement for renewable fuel in 2022 is 136 B liters, and can be met by conventional biofuels (corn ethanol) and advanced biofuels derived from feedstocks other than corn starch with a lifecycle GHG emission displacement of at least 50% compared to gasoline. Of the 136 B liters of the renewable fuel, the RFS requires that at least 80 B liters should be advanced biofuels. Advanced biofuel specifically excludes ethanol derived from corn starch even if corn ethanol were made to meet the GHG reduction threshold. It includes ethanol made from cellulose, hemicelluloses, lignin, sugar or any starch other than corn starch as long as it meets the GHG reduction requirement. Of these 80 B liters of the advanced biofuels, at least 60 B should be cellulosic biofuels derived from any cellulose, hemicelluloses or lignin and achieving a lifecycle GHG emission displacement of 60% compared to gasoline. Conventional biofuels produced from corn starch get capped at 56 B liters in 2022. Cumulative production of biofuels over the 2007-2022 period mandated by the RFS requires 1220 B liters of renewable fuel and at least 420 B liters of advanced biofuels. The amount of conventional biofuels cannot exceed 800 B liters during this period.

Sugarcane ethanol imported from Brazil can reduce GHG emissions by 70% relative to gasoline (Lasco and Khanna 2009; Macedo, Seabra and Silva 2008; Von Lampe 2006), and qualifies as an advanced biofuels. Thus, it can be used to meet the requirement for advanced biofuels. It also can compete with corn ethanol under the category of conventional biofuels if it has cost advantage over corn ethanol.

Under the RFS program, EPA proposed to new changes regarding to eligible land that can be used to produce renewable biomass in 2009. It requires that crops used to produce qualifying renewable fuels be harvested from agricultural land cleared or cultivated prior to December 2007. Land enrolled in the Conservation Reserve Program (CRP) can increase soil productivity, reduce soil erosion and improve ground and surface water quality, and is not allowed to be converted for the production of miscanthus and swithchgrass (EPA 2010). In essence, EPA capped the amount of land that can be used for agriculture at 2007 acreage level. If agricultural land exceeds the 2007 level, biofuel producers must prove that their feedstock did not come from newly converted land to qualify the definition of biofuels under the RFS2.

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

In addition to biofuel mandates and volumetric tax credits, the U.S. imposes trade barriers to restrict the imports of sugarcane ethanol from Brazil. The biofuel trade policy includes a 2.5% ad valorem tariff and a per unit tariff of \$0.14 per liter (authorized until January 2011). A key motivation for the establishment of the tariff is to offset a tax incentive for ethanol-blended gasoline. This incentive is currently valued at \$0.13 per liter of ethanol, and reduced to \$0.12 per liter in the FCEA of 2008. An exception to the tariff is the agreement of the Caribbean Basin Initiative (CBI) initiated by the 1983 Caribbean Basin Economic Recovery Act (CBERA). Under this agreement, ethanol produced from at least 50% agricultural feedstocks grown in CBI countries is admitted into the U.S. free of duty. If the local feedstock content is lower than the requirement, a tariff rate quota (TRQ) will be applied to the quantity of duty-free ethanol. Nevertheless, duty-free ethanol from CBI countries is restricted to no more than 0.2 B liters or 7% of the U.S. ethanol consumption.

To take advantage of this tariff-free policy, hydrous ethanol produced in other counties, like Brazil or European countries, can be imported to a CBI country and exported to the U.S. after dehydration. In 2007, total imports account for roughly 6% of U.S. consumption (25.7 B liters), with about 40% of the import from Brazil and approximately 60% routed through CBI countries to avoid the import tariff[2]. However, CBI countries have never reached the ceiling on their ethanol quota, partly due to insufficient capacity[3].

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.[4] Estimates of the market price of allowances over the 2009-2020 period differ across the two bills but is generally expected to be lower than $30 per ton of CO_2 equivalent with the upper bound set by the price at which allowances held in a strategic reserve will be auctioned (USDA 2009).

2.2 Previous Literature

2.2.1 Stylized Models

A number of studies have examined the effects of biofuel subsidy on fuel and food prices and social welfare using a stylized model. Gardner (2007) estimates the deadweight losses of the ethanol subsidy as opposed to a direct deficiency payment subsidizing corn producers. The estimates for the loss in social welfare due to the ethanol subsidy are $91M in the short run and $665 M in the long run. To offset the deadweight losses of the subsidy, the environmental benefits of ethanol would need to be valued at least $0.06 per liter of ethanol. However, he does not consider gasoline markets and substitutability between gasoline and ethanol. Using a partial equilibrium model in an open economy and assuming perfect substitutes between gasoline and ethanol, Rajagopal et al. (2007) estimate that the ethanol tax credit increases corn price by 21% while lowering the price of gasoline by 3%. They also find that the ethanol tax credit can be expected to result in a net gain in social welfare for the U.S. if the loss to U.S. gasoline producers is small (less than $10.3 B). de Gorter and Just (2009) analyze the interaction effects of the ethanol tax credit with farm subsidies. In their numerical simulation, they assume gasoline prices are exogenously given. As a result, the ethanol subsidy does not have impact on gasoline prices, and the market price for corn is determined by the price of gasoline and the tax credit. They find that the ethanol tax credit leads to a loss in social welfare of $1.3 B because of the revenue costs of the tax credit and the loss in surplus of corn consumers due to higher prices. Above studies do not consider externality costs associated with the consumption of fuel when evaluating the effect of the ethanol subsidy on social welfare.

Assuming imperfect substitutability between gasoline and ethanol in a closed economy, Khanna, Ando and Taheripour (2008) show that the optimal taxes to internalize environmental externalities should be imposed on gasoline ($0.02 per liter), ethanol ($0.02 per liter) and miles ($0.05 per kilometer). The ethanol subsidy of $0.13 per liter reduces carbon emissions by 5% and increases social welfare by $11.8 B relative to the baseline. In comparison to the optimal policy, the ethanol subsidy results in a $19 B loss in social welfare and increases carbon emissions by 20%. In considering environmental and fuel security externalities associated with the consumption of fuels, Vedenov and Wetzstein (2008) use a general equilibrium framework to find that the optimal subsidy for ethanol should be positive at $0.06 per liter, but the marginal external benefit of renewable fuel use is negative. That is because the ethanol subsidy increase total fuel consumption and GHG emissions by lowering overall price of the blended fuel.

A few studies have analyzed the combined effects of the ethanol subsidy and import tariffs on food prices and social welfare in open economy with trade in biofuels. Elobeid and Tokgoz (2008) use the partial equilibrium FAPRI model to show that current trade barriers have been effective in protecting domestic ethanol and agricultural industries, and trade liberalization and removal of the ethanol tax credits can mitigate the adverse effects on food prices due to the expansion in corn ethanol production. Lasco and Khanna (2009) use a stylized model to derive the optimal mix of trade and environmental policy instruments in the presence of environmental externalities assuming an imperfect substitutability of gasoline and ethanol. They find current ethanol policy of an ethanol tax credit and import tariff increases GHG emissions and decreases social welfare relative to non-intervention scenario.

Several studies have examined the economic effects of an RFS and other biofuel policies (Ando, Khanna and Taheripour 2010; de Gorter and Just 2007; de Gorter and Just 2008; de Gorter and Just 2010; Gallagher et al. 2003; Tyner and Taheripour 2007). Gallagher et al. (2003) analyze the implications of an RFS of 19 B liters of ethanol together with a ban on the use of MTBE as a fuel additive for fuel consumption and prices and social welfare. They find these policies lead to higher prices of the blended fuel, which in turn lowers gasoline consumption and price in 2015 by 5% and 2%, respectively, relative to the baseline. Social welfare (without including environmental benefits) decreases by 6% but emissions of air pollutants decline. de Gorter and Just (2007) examine the effects of a tax credit in the presence of a blend mandate assuming perfect substitutability between gasoline and ethanol. They show that the tax credit lowers the cost of fuel and would lead to an increase in gasoline consumption by 0.4% and a reduction in the price of the blended fuel by 2% in 2015. In the following work, they extend the analysis by incorporating ethanol imports to examine the effects of a tax credit and an import tariff in the presence of a blend mandate (de Gorter and Just 2008). They find the removal of import tariffs reduces domestic ethanol prices by 2.4% but increases world prices by 21% in 2015 in the presence of a binding blend mandate, and eliminating both the tariff and tax credit makes very little difference to fuel prices or consumption. Ando, Khanna and Taheripour (2010) show that a biofuel mandate with tax credits leads to a loss in social welfare by $61 B relative to the optimal policy (a carbon tax and a miles tax). The mandate also reduces the price of the blended fuel and this offsets a part of the reduction in GHG emissions that would have been achieved otherwise.

In comparing several biofuel policies, Tyner and Taheripour (2007) show that variable subsidies should be provided to blenders while considering crude oil prices in the presence of the RFS mandates to provide a risk sharing mechanism with fuel consumers. However, de Gorter and Just (2010) state that the RFS mandate alone is a preferred biofuel policy while biofuel subsidies can have negative effects on the environment and social welfare by lowering the price of the blended price.

2.2.2 Land Use Models

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 (corn price decreases about 1.5%) 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). They show that the mandate will lead to major increases in the prices of corn and soybeans by 10%, and 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 afforestation. 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), and find that \$50 per ton of CO2e would lead to increases in the prices of corn and soybeans by 51% and 13%, respectively. FASOM is used by EPA to simulate the impacts of implementing revised Renewable Fuel Standard (RFS2) relative to 2007 Annual Energy Outlook (AEO2007) reference case (EPA 2010). They find that the RFS mandates would lead to a reduction in GHG emissions by 138 M metric tons. Corn and soybeans prices in 2022 would increase by 8% and 10%, respectively, while gasoline price decreases by 2.4 cents per gallon. Total social welfare in 2022 is \$13-26 B higher than the reference level.

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, Tyner and Birur 2010) and imperfect substitutability between gasoline and ethanol (Birur, Hertel and Tyner 2008). Reilly, Gurgel and Paltsev (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.

2.3 Contribution of the Dissertation

2.3.1 Theoretical Model

The theoretical model developed in this study contributes to the existing literature of economic analysis of biofuel policies. We models gasoline and biofuels as imperfect substitutes in producing the blended fuels. Some studies in the literature (Elobeid and Tokgoz 2008; Vedenov and Wetzstein 2008) have assumed that gasoline and biofuels are complements when ethanol is considered as an additive while other studies (such as de Gorter and Just 2009; de Gorter and Just 2010) assume that gasoline and biofuels are perfect substitutes. However, the assumption of perfect substitutability between gasoline and biofuels holds only if the fuel markets are not constrained by the fleet structure and there is no limit for blenders to blend gasoline with biofuels. To accommodate with the prevailing market conditions in the U.S, we model gasoline and biofuels as imperfect substitutes to produce the blended fuel, and we do sensitivity analysis of the model results using alternative values of the elasticity of substitution between gasoline and biofuels.

We consider externality costs caused by GHG emissions from the consumption of gasoline and biofuels that are differentiated by their GHG intensities. Many papers in the existing literature (de Gorter and Just 2009; de Gorter and Just 2010; Elobeid and Tokgoz 2008; Gardner 2007) do not consider environmental effects of biofuel policy, and compare social welfare with non-government intervention. To internalize the externality costs, we show that a higher carbon tax should be imposed on gasoline relative to biofuels. We also use this framework to analyze the effect of a carbon tax on gasoline consumption due to the substitution effect between gasoline and biofuels and the output effect because of increase cost of miels. We compare social welfare under biofuel policies with both non-government intervention and a carbon tax.

In addition, we examine the effect of climate and biofuel policies on food prices by linking agricultural and fuel sectors with a limited availability of cropland that can be used to produce food crops and fuel crops. Existing literature (such as de Gorter and Just 2009; Gardner 2007; Lasco and Khanna 2009; Rajagopal et al. 2007) assumes a supply curve for corn production that can be used for the demand of food and biofuels. The framework developed here can be used to analyze the effect of biofuel policy on food prices and land rent, and can be easily generalized to examine the impacts on other crop prices.

2.3.2 Land Use Model

The numerical land use model developed in this study differs from the existing models in the literature in several aspects. It allows 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.[5] 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, this study examines the implications of a range of substitutability between gasoline and ethanol and implicitly derives 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). It allows biofuel production to have a feedback effect on gasoline prices and thus on the demand for biofuels (as in Hayes et al. 2009).

The U.S. accounts for 23% of world petroleum consumption, and about 57% of the consumption is imported from the rest of the world (EIA 2010); thus the change in U.S. gasoline demand can significantly affect world gasoline prices. To capture the effect of biofuel policy on the world gasoline price, this study considers gasoline supply from domestic producers and the rest of world. The sensitivity of model results to the magnitude of the elasticities of supply of gasoline is also examined.

Crop yield changes over time influence the land needed to meet food and fuel needs to meet biofuel mandates. Dumortier et al. (2009) show that introduction of even a 1% increasing trend in corn yield in the FAPRI model can substantially reduce the corn acreage in response to changes in gasoline and biofuel prices. This study allows 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, this study uses the estimated own and cross price crop elasticities to limit the flexibility of crop acreage changes (Huang and Khanna 2010).

Unlike Baker et al. (2009) and Ugarte et al. (2009) who consider the impact of climate policies assuming the RFS is implemented, this study considers 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. This study quantifies 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.

Chapter 3: A Conceptual Model of Fuel and Food

This chapter develops a stylized model of the food and fuel sectors linked by a limited availability of land to produce food and fuel crops to analyze the mechanisms by which biofuel and climate policies affect consumer choices. The goal is not to model all the implementation details of these policies, rather use relevant stylized facts about them to analyze their implications for the agricultural and fuel sectors. Some of the parameters likely to influence the impacts of these policies on fuel consumption and GHG emissions are also identified in the conceptual framework.

3.1 The Model

We consider an economy with a representative consumer that demand food (f) and transportation (m). The representative consumer has the option to choose the consumption of blended fuel (b) that is produced by blending gasoline (g) and biofuels (e). At individual consumer level, the two fuels can be perfect substitutable up to a 10% level with a conventional vehicle. For an individual consumer with a flex fuel vehicle the two fuels can be up to an 85% blend. At aggregate level, we consider a representative consumer that owns a vehicle fleet that consists of a mix of the two types of vehicles; only 2.9% of vehicles in 2007 were flex vehicles (EIA 2010). His ability to substitute g and e is, therefore, limited by the mix of vehicles. It is also limited by the available ethanol distribution network and infrastructure for retail ethanol sales. We, therefore, consider gasoline and ethanol to be imperfectly substitutable at the aggregate level to produce the blended fuel, and examine the implications of the extent of substitutability on the consumption of the two fuels. The production of the blended fuel is represented using a constant elasticity of substitution function $b(g,e)=[ag^{\rho}+(1-a)e^{\rho}]^{1/\rho}$. 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.[6]

The production of transportation measured in vehicle miles traveled (VMT) can be expressed as $m = \gamma b$, where γ is efficiency parameter denoting the amount of miles generated from one gallon of the blended fuel. Both fuels generate negative externalities, namely the GHG emissions; where GHG emissions generated by ethanol are lower than the GHG emissions 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.

The GHG emissions generated from a liter 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, $f + e \leq \overline{L}$. 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.

3.2 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:

$$\underset{g,e,f}{Max} \quad U(m) + U(f) - t(\delta_g g + \delta_e e) - c(g) - c(e) - c(f) \tag{3.1}$$

subject to $m = rb$, $b=[ag^{\rho} + (1-a)e^{\rho}]^{1/\rho}$ 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:

$$L = U(m) + U(f) - t(\delta_g g + \delta_e e) - c(g) - c(e) - c(f) + \lambda(\overline{L} - f - e) \tag{3.2}$$

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

$$U^{'}(m)m_g - \delta_g t - c^{'}(g) = 0 \tag{3.3}$$

$$U^{'}(m)m_e - \delta_e t - c^{'}(e) - \lambda = 0 \tag{3.4}$$

$$U_f^{'}(f) - c^{'}(f) - \lambda = 0 \tag{3.5}$$

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 (3.5) 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 (3.3) and (3.4) suggest that environmental 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 (3.3)-(3.5) as shown in Appendix A.

$$\frac{dg}{dt} < 0 \tag{3.6}$$

As expected, we find that a carbon tax would unequivocally lower gasoline consumption by raising the gasoline price, increasing the marginal cost of VMT and lowering demand for VMT.

$$\frac{de}{dt} = \frac{1}{H}\{\frac{s_g}{g}.\frac{1}{\varepsilon_m^d}(\delta_e(p_g + \delta_g t) - \delta_g(c^{'}(e) + \delta_e t))\} - \frac{1}{H}\{\frac{I_m s_g s_e}{g^2 e\sigma}(\frac{\delta_e s_g e}{\sigma EMP_e} + \delta_g g) + \delta_e \frac{p_g}{\varepsilon_g^s g}\} \tag{3.7}$$

where *H>0* is the determinant of the matrix derived from total differentiation of the first order conditions (see equation A2 in Appendix A). We define $I_m = P(m).m$ as the expenditure on miles, s_e and s_g are cost shares of fuels on miles expenditure, ε_m^d and ε_g^s 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 $c'(g)$).[7] We define $EMP_g \equiv -m_{gg}.g/m_g$ >0 and $EMP_e \equiv -m_{ee}.e/m_e$ >0 based on Caswell and Zilberman (1986) and refer to them as the elasticity of the marginal productivity of *g* and *e*, respectively.

A carbon tax can reduce emissions in two ways, by inducing a reduction in miles and a substitution of ethanol for gasoline. Equation (3.7) shows that its net impact on the consumption of biofuels depends on the magnitudes of the two terms in brackets. The first term in (3.7) in brackets is always positive and increases in magnitude as the elasticity of miles becomes smaller and as the term $(\delta_e(p_g+\delta_g t)-\delta_g(c^{'}(e)+\delta_e t))$ becomes larger. This term indicates the cost-effectiveness of biofuels in reducing GHG emissions relative to gasoline. This cost effectiveness increases as the gap between δ_e and δ_g increases while the gap between $c'(e)>p_g$ remains low. The second term in (3.7) determines the substitution effect of the carbon tax, which depends on the effect of tax on the price of the fuels and the ease with which biofuels can be substituted for gasoline. Since biofuels are likely to be more expensive than gasoline, this substitution effect raises the marginal cost of VMT which will reduce miles consumption and therefore demand for all fuels.

Thus, a carbon tax leads to an increase in ethanol consumption if the elasticity of substitution $\sigma = \infty$ and if $\varepsilon_g^s = \infty$ because in this case the second term in (3.7) is zero. When the supply of gasoline is infinitely elastic and gasoline and ethanol are perfectly substitutable, a small increase in its relative price 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 reduces GHG emissions as shown in equation (A8) in Appendix A. 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 as shown below.

$$\frac{dGHG}{dt}=\frac{1}{H}\{\delta_g^2[\frac{p_f}{\varepsilon_f^d f}-\frac{c^{'}(f)}{\varepsilon_f^s f}-\frac{I_m s_e}{e^2}EMP_g-\frac{c^{'}(e)}{\varepsilon_e^s e}]-\delta_e^2[\frac{I_m s_g}{g^2}EMP_g+\frac{c^{'}(g)}{\varepsilon_g^s g}]-\frac{2\delta_g\delta_e s_g s_e I_m}{ge\sigma}+\frac{I_m(\delta_g g s_e-\delta_e e s_g)^2}{g^2e^2\varepsilon_m^d}\}<0 \tag{3.8}$$

$$\frac{df}{dt}=-\frac{de}{dt}\text{, and }\frac{d\lambda}{dt}=(\frac{c'(f)}{\varepsilon_f^s f}-\frac{p_f}{\varepsilon_f^d f})\frac{de}{dt} \tag{3.9}$$

Equation (3.9) 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.

3.3 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.

3.3.1 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

$$L=U(m(g,\bar{e}))+U(f)-t(\delta_g g+\delta_e e)-c(g)-c(\bar{e})-c(f)+\lambda(\bar{L}-f-\bar{e}) \tag{3.10}$$

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 costs for low levels of gasoline consumption. Thus, at low levels of fuel consumption blenders can be expected to price fuel based on its average cost (if average cost is greater than the marginal cost) in order to avoid negative profits. In this case VMT will be determined by the average cost of a mile rather than its marginal cost. 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 C and discussed here. First order condition (3.3) is now as follows, while condition (3.5) is unchanged:

$$U_m' m_g - c'(g) = 0 \tag{3.11}$$

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

$$\frac{dg}{d\bar{e}} = \frac{-1}{K} . \frac{I_m s_e s_g}{g\bar{e}} \left(\frac{1}{\varepsilon_m^d} + \frac{1}{\sigma}\right) \tag{3.12}$$

$$\frac{dm}{d\bar{e}} = \frac{-s_e m}{Kg\bar{e}} \left\{\frac{I_m s_g^2 s_e}{g\sigma^2 EMP_e} + \frac{I_m s_g^2}{g\sigma} + \frac{p_g}{\varepsilon_g^s}\right\} > 0 \tag{3.13}$$

where K is the determinant of the matrix under the consumption mandate and always negative as shown in Appendix B. A consumption mandate raises the cost of biofuels while it lowers the price of gasoline if ε_g^s is less than infinity (or leaves it unchanged if gasoline supply is infinitely elastic). The expression in (3.12) must be negative because a positive sign implying that gasoline consumption increases with the mandate would be inconsistent with the lower cost per mile required for VMT to increase the consumption of the additional gasoline and biofuel as shown in equation (3.13). A negative sign of the expression in (3.12) implies $\left|\varepsilon_m^d\right| < \sigma$. Thus 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 C). Additionally, expression in (3.13) shows that the mandate would always lead to an increase in the consumption of VMT. A key difference between a carbon tax and a mandate is that the latter does not raise the price of gasoline and may even lower it. However, like a carbon tax its effect on gasoline consumption is negative although for different reasons.

$$\frac{dGHG}{d\bar{e}} = \frac{1}{Kg\bar{e}}\{I_m s_g [\frac{\delta_e s_g \bar{e} - \delta_g s_e g}{g\varepsilon_m^d} - \frac{\delta_e s_g s_e \bar{e}}{gEMP_e \sigma^2} - \frac{\delta_g s_e}{\sigma}] - \frac{\delta_e p_g \bar{e}}{\varepsilon_g^s}\} \tag{3.14}$$

The effect of the consumption mandate on GHG emissions depends (among other terms) on ε_m^d, σ, and ε_g^s. The first term in the square bracket in (3.14) 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 the mandate. Similar conditions are shown in the case that average cost pricing of blended fuel is used.

Equations (3.15) and (3.16) indicate that the biofuel mandate will decrease food production and increase land rent given a limited amount of land resource.

$$\frac{df}{d\bar{e}} < 0 \tag{3.15}$$

$$\frac{d\lambda}{d\bar{e}} > 0 \tag{3.16}$$

3.3.2 Biofuel Consumption Mandate and Biofuel Subsidy

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

$$L = U(m(g,\bar{e})) + U(f) - t(\delta_g g + \delta_e e) - c(g) - c(\bar{e}) - s\bar{e} - c(f) + \lambda(\bar{L} - f - \bar{e}) \tag{3.17}$$

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 $P(m) = f(p_e, p_g)$.

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

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

$$\frac{dg}{ds} = \frac{-g\varepsilon_m^d}{p_e + (\frac{a}{1-a})^{\sigma} p_e^{\sigma} p_g^{1-\sigma}} > 0 \tag{3.18}$$

We can similarly show that:

$$\frac{df}{ds} = 0 \tag{3.19}$$

$$\frac{d\lambda}{ds} = 0 \tag{3.20}$$

$$\frac{dGHG}{ds} = \frac{-\delta_g g \varepsilon_m^d}{p_e + (\frac{a}{1-a})^{\sigma} p_e^{\sigma} p_g^{1-\sigma}} > 0 \tag{3.21}$$

$$\frac{dm}{ds} = \frac{-ms_g \varepsilon_m^d}{p_e + (\frac{a}{1-a})^{\sigma} p_e^{\sigma} p_g^{1-\sigma}} > 0 \tag{3.22}$$

With a binding mandate, equations (3.19) and (3.20) indicate that a subsidy has no impact on food consumption and land rent since production of biofuels and food does not change. The subsidy increases (or reduces the reduction in) the consumption of gasoline and 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.

In summary, a carbon tax would reduce gasoline consumption by increasing gasoline price and reducing the consumption of VMT through raising the marginal cost of VMT. The tax would also induce a switch away from gasoline to biofuels to lower overall GHG emissions. While a biofuel mandate would reduce gasoline consumption, the effects on GHG emissions are uncertain. Unlike a carbon tax raises the marginal cost of miles, the effect of the mandate on miles consumption depends on the demand elasticity of miles, elasticity of substitution between gasoline and biofuels and the supply elasticity of gasoline. A biofuel mandate accompanied with subsidies would lower the marginal cost of miles and create incentives to increase the consumption of the blended fuel. As a result, gasoline consumption and GHG emissions would increase.

3.4 Welfare Effects of a Carbon Tax and Biofuel Policies

Each of these climate and biofuel policies is expected to have different effects on externality costs from GHG emissions and social groups that include consumers and producers in the agricultural and fuel sectors, and the government. In fuel sector, a carbon tax is expected to decrease miles consumers' surplus by raising fuel prices, and reduce gasoline producers' surplus by lowering gasoline consumption and producer's price of gasoline. In a closed economy without gasoline trade with the rest of the world, domestic gasoline producers would have to bear all the loss due to the tax. In agricultural sector, agricultural producers' surplus and agricultural consumers' surplus would increase and decrease, respectively, if the carbon tax increases the demand for biofuels. That is because increasing demand for biofuels will raise crop prices by increasing the demand for fuel crops and shifting cropland from food crops to fuel crops. Externality costs due to GHG emissions are likely to decrease while government revenue will increase from the collection of the carbon tax. Overall domestic social welfare in agricultural and fuel sectors under a carbon tax is expected to be higher than that under no government intervention. In an open economy, gasoline can be imported from the rest of the world, and domestic gasoline producers and foreign gasoline producers will bear the loss together. Foreign gasoline producers are likely to take a larger portion of the loss since about 60% of U.S. domestic gasoline consumption is imported from the rest of the world (EIA 2010). However, welfare effects of a carbon tax in open economy are complicated by the fact that the carbon tax would affect terms of trade and tariff revenue (Krutilla 1991). As a result, the welfare effect of a carbon tax in an open economy is theoretically ambiguous relative to that in a closed economy.

A biofuel mandate will lead to higher costs of biofuels by requiring the consumption of biofuels beyond the levels that can be achieved by the free market. It will also lead to a greater displacement of gasoline than a carbon tax policy. That will result in a greater surplus loss for both domestic gasoline producers and foreign gasoline producers in an open economy relative to a carbon tax with foreign gasoline producers bearing a larger share of the surplus loss. The impacts of the biofuel mandate on miles consumers and externality costs are uncertain relative to a carbon tax. Miles consumers under a mandate can be worse off than a carbon tax if the cost of biofuel production is high and the competition for cropland is severe. On the other hand, miles consumers can be better off than a carbon tax if the displacement of biofuels for gasoline leads to a larger reduction in gasoline price. Externality costs under a biofuel mandate can be lower than that under a carbon tax if the displacement of gasoline with biofuels is large with a high elasticity of substitution between gasoline and biofuels and a flatter gasoline supply curve. Moreover, since the biofuel mandate requires more cropland to produce fuel crops, it will result in larger increases in crop prices than a carbon tax. Agricultural producers and agricultural consumers would be better off and wore off, respectively, than a carbon tax policy. With an open market assumption for gasoline, the welfare effect of the mandate relative to a carbon tax is theoretically ambiguous. We rely on the numerical model developed in the following chapter to analyze the welfare effects of the RFS and compare it to a carbon tax.

A biofuel mandate accompanied with subsidies would lower the price of the blended fuel and increase the consumption of gasoline. Miles consumers would be better off relative to a mandate alone while gasoline producers would also be better off because of increased gasoline consumption and price. Externality costs would be higher due to additional GHG emissions from increased gasoline consumption relative to a mandate alone. In agricultural sector, agricultural consumers and producers would not be affected by the subsidies since the biofuel mandate is still binding. The subsidy on biofuels will increase government expenditure than a mandate alone. In comparison to a mandate alone, a biofuel mandate and subsidies will generate lower social welfare than a mandate alone.

The above discussion of the welfare effects under alternative climate and biofuel policies assumes one type of biofuels in the market. When cellulosic feedstocks (such as crop residues and dedicated energy crops) are introduced into the production of biofuels and the RFS mandates are flexible for different types of biofuels, a higher subsidy to cellulosic biofuels can change the mix of biofuels in favor of cellulosic biofuels. That would reduce externality costs and mitigate the adverse effects on food consumers by using high-yielding energy crops to meet the mandates. In this case, government expenditure will depend on the quantity of production of corn ethanol and cellulosic biofuels. The effect of biofuel mandates and subsidies on total social welfare is ambiguous relative to a mandate alone.

In comparison to a carbon tax, the effects of biofuel policy on social welfare are ambiguous. However, the framework developed here can be used numerically to determine the effects of biofuel mandates and subsidies based on data on the consumption and prices of agricultural commodity and gasoline and biofuels, and the RFS mandates. The simulation model developed in the next chapter will be utilized to reveal the effects of biofuel policy on social welfare and GHG emissions.

Chapter 4: A U.S. Agricultural Sector Model: Biofuel and Environmental Policy Analysis Model (BEPAM)

The conceptual model described in Chapter 3 shows the effects of various parameters on fuel and biofuel consumption decisions and GHG emissions. We expand the simplified representation of the fuel and agricultural sectors above by developing a U.S. agricultural sector model to simulate the U.S. agricultural and fuel sectors and formation of market equilibrium in the commodity markets. We refer to this model as a Biofuel and Environmental Policy Analysis Model (BEPAM). BEPAM is a dynamic, multi-market equilibrium model, which analyzes the markets for fuel, biofuel, food/feed crops and livestock for an extendable future period (currently set for 2007-2022) in the U.S. We consider biofuels produced not only from corn but also from several cellulosic feedstocks. We also incorporate sugarcane ethanol imports from Brazil and CBI countries. In gasoline markets, we distinguish gasoline supply not only from domestic production but the rest of the world. The spatial heterogeneity in yields, costs of production and land availability is also incorporated by assuming each Crop Reporting District (CRD) as a decision-making unit. We include cropland and marginal land in the model, and assume that total cropland availability in each CRD can change in response to changes in crop prices. Food and fuel prices are endogenously determined annually and used to update price expectations, cropland acreage and land use choices. Life cycle analyses are used to estimate the GHG intensity of alternative fuels and emissions due to changes in cropping patterns at the CRD level. We currently do not include GHG emissions due to indirect land use changes and therefore underestimate the GHG intensity of biofuels.

4.1 Description of BEPAM

BEPAM is a dynamic multi-market, multi-period, price-endogenous, nonlinear mathematical programming model of the agricultural and transportation fuel sectors in the U.S. The agricultural sector in BEPAM includes several major row crops, livestock and bioenergy crops (crop residues and perennial grasses) and distinguishes between biofuels produced from corn and cellulosic feedstocks. 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 (McCarl and Spreen 1980; Takayama and Judge 1971). This model is designed specifically to analyze the implications of biofuel and climate policies on land use patterns, commodity markets, and the environment.

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

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 constant elasticity of substitution (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 US 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 hypothetical (synthetic) mixes to offer increased planting flexibility beyond the observed levels and allow land uses that might occur in response to the projected expansion in the biofuels industry and related increases in corn and cellulosic biomass production. Each synthetic mix represents a potential crop pattern generated by using the estimated own and cross price crop acreage elasticities and considering a set of price vectors where crop prices are varied systematically. These elasticities are estimated econometrically using historical , county-specific data on individual crop acreages for the period 1970-2007 as described in Huang and Khanna (2010).

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

The endogenous variables determined by the model include: (1) commodity prices; (2) production, consumption, export and import quantities of crop and livestock commodities and fuel and biofuels; (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.

4.2 The Algebraic Equations of BEPAM

We describe the algebraic form of the numerical model using lower case symbols to denote the exogenous parameters and upper case symbols to represent endogenously determined variables. The objective function is the sum of discounted consumers' and producers' surpluses obtained from production, consumption and trade of the crop and livestock products plus the surplus generated in the fuels sector over the 16-year planning horizon 2007-2022 and the terminal values of standing perennial grasses in 2022. The algebraic expression is given explicitly in (4.1):

$$
\begin{aligned}
Max:&\sum_{0}^{T} e^{-rt}\{ \sum_{z}\int_{0}^{DEM_{t,z}} f^{z}(.)d(.)+\sum_{z}\int_{0}^{EXP_{t,z}} f^{z}(.)d(.)-\sum_{z}\int_{0}^{IMP_{t,z}} f^{z}(.)d(.)+\int_{0}^{MIL_{t}} f^{z}(.)d(.)\\
&-\sum_{r,q} rc_{r,q}ACR_{t,r,q}-\sum_{r,p} pc_{r,p}ACR_{t,r,p}-\sum_{r,q} rs_{r,q}ACR_{t,r,q}-\sum_{r,p} cc_{r}\Delta ACR_{t,r,p}\\
&-\sum_{k} lc_{k}LIV_{t,k}-\sum_{i} sc_{i}PRO_{t,i} \qquad (4.1)\\
&-\int_{0}^{GAS_{t,o}} f_{o}^{g}(.)d(.)-ec_{c}ETH_{t,c}-ec_{b}ETH_{t,b}\}\\
&+e^{-rT}\sum_{r,p}(v_{r,p}-w_{r})ACR_{T,r,p}
\end{aligned}
$$

The first integral term in line of (4.1) represents the areas under the domestic demand functions from which consumers' surplus is derived. Each integral is associated with a crop, livestock, or processed commodity for which a domestic market demand is considered ($DEM_{t,z}$ denotes the endogenous domestic demand variable in year *t*; $z = \{i, j, k\}$ } denotes the index set for crop commodities (*i*), processed products from crops or sugarcane ethanol (*j*), and livestock commodities (*k*); $f^{z}(.)$ denotes the inverse demand function for the commodity involved; and *d*(.) denotes the integration variable). The next two integral terms account for the areas under the inverse demand functions for exports, $EXP_{t,z}$, and the areas under the import supply functions $IMP_{t,z}$ (such as sugar and sugarcane ethanol). The last integral term represents the area under the inverse demand function for miles traveled (denoted by MIL_{t}). The demand functions for crop products, livestock products and miles traveled are all characterized by linear demand functions in the current version, but other functional forms, such as constant elasticity demand functions, can be incorporated without difficulty.

The second line in (4.1) includes the production costs of row crops, perennial crops and crop residues collected for biofuel production, and land conversion costs for marginal land converted to the production of perennial crops. The land allocated to row crops and perennial crops (acreage) in region *r* and year *t*, denoted by $ACR_{t,r,q}$ and $ACR_{t,r,p}$, respectively, may use one of the various production practices which differ by crop rotation, tillage, and irrigation. Fixed input-output coefficients (Leontief production functions) are assumed for both row crops and perennial crops production. The third term represents the cost of collected crop residues (biomass for cellulosic biofuel production) and involves the management options for row crops that produce biomass (specifically, corn stover and wheat straw). The amount of marginal land converted for perennial grasses are denoted by $\Delta ACR_{t,r,p}$ and cc_r represents the cost per unit of marginal land conversion. The last term denotes the costs of converted marginal land (such as idle land and crop pasture land) for perennial crops. The land conversion costs include costs for land clearing, wind rowing and any necessary activities for seedbed preparation.

The third line in (4.1) includes the costs associated with livestock activities. The amount of livestock is represented by $LIV_{t,k}$, and lc_k denotes the cost per unit of livestock category *k* (again employing Leontief production functions) that is assumed to be the same across all regions. The second term represents the total cost of converting primary crops (corn, soybeans, and sugarcane) to secondary (processed) commodities (oils, soymeal, refined sugar, HFCS and DDGS). The amount of processed primary crop *i* in year *t* is denoted by $PRO_{t,i}$, and sc_i denotes the processing cost per unit of *i*.

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

In the model, we assume that the consumers obtain utility from vehicle miles traveled (MIL_t), which is produced by blending gasoline ($GAS_{t,o}$), corn ethanol ($ETH_{t,c}$), cellulosic ethanol ($ETH_{t,b}$) and sugarcane ethanol ($IMP_{t,s}$). Gasoline and ethanol are assumed to be imperfect substitutes in miles production while corn ethanol and cellulosic ethanol are perfect substitutes. The total amount of miles generated by use of all sources of fuels is formulated using a constant elasticity production function as shown in equation (4.2) below:

$$MIL_t = \gamma_t[\alpha_t(ETH_{t,c} + ETH_{t,b} + IMP_{t,s})^{\rho} + (1-\alpha_t)(\sum_o GAS_{t,o})^{\rho}]^{1/\rho} \quad \text{for all } t \qquad (4.2)$$

The regional material balance equations link the production and usage of primary crops, as shown in constraint (4.3) for primary crop product *i* produced and marketed by region *r*:

$$MKT_{t,r,i} + \{CE_{t,r}\}_{|i=corn} \le \sum_j y_{r,q,i} ACR_{t,r,q} \quad \text{for all } t,\ r\ ,i \qquad (4.3)$$

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

The amount of primary crop *i* available in the market (excluding the corn used for ethanol) comes from domestic regional supply ($MKT_{t,r,i}$). This total amount is either consumed domestically ($DEM_{t,i}$), exported ($EXP_{t,i}$), processed to secondary commodities ($PRO_{t,i}$), or used for livestock feed ($FED_{t,i}$). This is expressed in constraint (4.4) below:

$$DEM_{t,i} + PRO_{t,i} + FED_{t,i} + EXP_{t,i} \leq \sum_{r} MKT_{t,r,i} \quad \text{for all } t, i \tag{4.4}$$

Similar to (4.4), a balance equation is specified for each processed commodity. Like primary commodities, processed commodities can also be consumed domestically, exported, or fed to animals, as shown in constraint (4.5) below:

$$DEM_{t,j} + FED_{t,j} + EXP_{t,j} \leq \upsilon_{i,j} PRO_{t,i} + \{\sum_{r} \upsilon_{i,j} CE_{t,r}\}_{j=ddg,i=corn} \quad \text{for all } t, j \tag{4.5}$$

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

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

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

$$E_{t,c} = \alpha \sum_{r} CE_{t,r} \quad \text{for all } t \tag{4.6}$$

$$E_{t,b} = \beta(\sum_{r,p} by_{r,p} AC_{t,r,p} + \sum_{r,q} ry_{r,q} AC_{t,r,q}) \quad \text{for all } t \tag{4.7}$$

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

Land is the only primary production factor considered in the model. In each region, the total amount of land used for all agricultural production activities cannot exceed the available land ($al_{t,r}$), which is specified separately for irrigated and non-irrigated land. Due to the steady increase in ethanol consumption the demand for agricultural land is expected to increase through the conversion of some marginal lands (not currently utilized) to cropland. The extent of conversion is assumed to depend on variations in crop prices over time. Therefore, in the model we determine the agricultural land supply 'endogenously'. Specifically, for a given year *t* in the planning horizon 2007-2022, we solve the model assuming a fixed regional land availability for each year of the 10-year production planning period considered in that run. From the resulting multi-year equilibrium solution, we take the first-year values of the endogenous commodity prices and use them to construct a composite commodity price index, CPI. Based on the CPI generated thereby we adjust the land availability for the subsequent run (which considers another 10-year planning period starting with year *t*+1). The land constraint is shown in (4.8).

$$\sum_{q} ACR_{t,r,q} + \sum_{p} ACR_{t,r,p} \le al_{t,r} \qquad \text{for all } t\ , r \tag{4.8}$$

To prevent unrealistic changes and extreme specialization in land use, which may be particularly serious at regional level, we restrict farmers' planting decisions to a convex combination (weighted average) of historically observed acreage patterns ($h_{r,ht,i}$) where subscript *ht* stands for the observed time periods prior to the base year. Historical land uses may be valid when simulating farmer's planting decisions under 'normal' conditions. However, they maybe too restrictive for future land uses given the increased demand for ethanol and unprecedented land use patterns that are likely to occur in the future to produce the required biomass crops. To address this issue we introduce 'hypothetical' acreage patterns ($h'_{r,n,i}$) for each row crop and each region. To generate hypothetical acreage patterns (crop mixes), we first use the historical data on prices and acreages of row crops in each region to estimate acreage elasticities for each row crop with respect to its own price and cross-price changes while controlling other factors, such as social- economic changes and time trend. Then we estimate a number of hypothetical acreages using these price elasticities and considering a systematically varied set of crop prices. The resulting set of actual and hypothetical crop mixes are used in constraint (4.9) to limit the flexibility in planting decisions, where $\theta_{i,q}$ represents the share of row crop *i* in production activity *q* and $W_{t,r,*}$ represents the weight assigned to historical or hypothetical crop mixes. The latter are defined as variables to be endogenously determined by the model.

$$\sum_{q} \theta_{i,q} ACR_{t,r,q} = \sum_{ht} h_{r,ht,i} W_{t,r,ht} + \sum_{n} h'_{r,n,i} W_{t,r,n} \quad \text{for all } t\ ,r\ ,i \tag{4.9}$$

The sum of the endogenous weights assigned to individual mixes must be less than or equal to 1 (convexity requirement), as shown in equation (4.10).

$$\sum_{ht} W_{t,r,ht} + \sum_{n} W_{t,r,n} \leq 1 \quad \text{for all } t\ ,r \tag{4.10}$$

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

Since miscanthus is a non-native grass species, a large scale of miscanthus production may have unforeseen impacts on biodiversity and water quality. To prevent extreme specialization in the production of perennial grasses in some regions, we restrict the land allocated to perennial grasses not to exceed 25% of total land availability in each region ($al_{t,r}$). The constraint is shown in (4.11).

$$\sum_{p} ACR_{t,r,p} \leq 0.25 * al_{t,r} \quad \text{for all } t, r \tag{4.11}$$

In the livestock sector, we define production activity variables (number of animals) at national level for each category of livestock except the beef and dairy cattle. Cattle production is given special emphasis in the model for two reasons. First, cattle require grazing land, therefore compete with crop production activities on total land in each region. Second, besides requirements of feed crops directly fed to different types of livestock, DDGS (a byproduct of corn ethanol production) is also used as a feed item that may substitute soymeal (both supplying protein). The regional cattle production activities are aggregated in (4.12) to obtain the total cattle activity at national level:

$$LIV_{t,cattle} = \sum_{r} CTL_{t,r} \quad \text{for all } t \tag{4.12}$$

where $CTL_{t,r}$ is the number of cattle stock in region *r* and year *t*. Cattle supply is constrained by the grazing land availability. Therefore, for each region we specify the grazing rates and the supply of grazing land, $GL_{t,r,g}$, where *g* denotes the type of grazing land (namely pasture land, forest land and cropland that can be used for grazing -such as wheat and oats). The amounts of other livestocks (chicken, turkey, lamb, pork and eggs) are also constrained by historical numbers at the national level. Constraint (4.13) below relates the usage of grazing land and cattle activity in each region:

$$CTL_{t,r} \leq \sum_{g} GL_{t,r,g} / ga_{r,g} \quad \text{for all } t, r \tag{4.13}$$

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

Equations (4.14) and (4.15) establish the balances between nutrition needs of livestock activities, in terms of protein and calories, and the amounts of nutrients provided by primary feed crops (grains) and byproducts of crops processing (i.e., soymeal and DDGS):

$$nr_{k,nu}LIV_{t,k} = \sum_i nc_{i,nu}F_{t,i,k} + \sum_j nc_{j,nu}F_{t,j,k} \text{ for all t, k} \tag{4.14}$$

$$FED_{t,z} = \sum_k F_{t,z,k} \text{ for all } t,\ k \text{ and } z = i, j \text{ used for feed} \tag{4.15}$$

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

To avoid unrealistic changes in feed mixes, we impose historical feed mixes used by all livestock categories. Constraints (4.16) and (4.17) constrain the consumption of feed to be within a convex combination of historical feed uses.

$$FED_{t,z} = \sum_{ht} hf_{z,ht}WF_{t,ht} \tag{4.16}$$

$$\sum_{ht} WF_{t,ht} \leq 1 \tag{4.17}$$

Soybean meal and *DDGS* are substitutes in the provision of protein up to a certain share level. Because the share of *DDGS* in total feed consumption of each livestock category is restricted (Babcock, Hayes and Lawrence 2008), we impose appropriate upper bounds for DDGS to reflect this aspect of feeding practices.

Livestock commodities can be consumed domestically or exported. The total supply of each livestock commodity is then related to the respective livestock production activity through a fixed yield coefficient, denoted by $ly_{k,s}$. Constraint (4.18) establishes this relationship:

$$DEM_{t,k} + EXP_{t,k} \leq \sum_{s} ly_{k,s} LIV_{t,s} \quad \text{for all } t,\ k \tag{4.18}$$

Chapter 5: Data

The simulation 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) at county level. We then aggregate crop yields and production costs to CRD level to reduce the timing of solving the numerical model. About 280 CRDs are included in this 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.

5.1 Yields and Costs of Bioenergy Crops

BEPAM considers two dedicated bioenergy crops, switchgrass (*Panicum viragatum*) and miscanthus (*Miscanthus* × *giganteus*), which have been identified as among the best choices for high yield potential, adaptability to a wide range of growing conditions and environmental benefits in the U.S. and Europe (Gunderson, Davis and Jager 2008; Heaton, Dohleman and Long 2008; Lewandowski et al. 2003). Both grasses have high efficiency of converting solar radiation to biomass and in using nutrients and water, and have good pest and disease resistance (Clifton-Brown J, Y-C and TR 2008; Semere and Slater 2007).

Switchgrass is a warm season perennial grass native to North America while Miscanthus is a perennial rhizomatous grass non-native to the U.S. A key concern with a large-scale introduction of a non-native grass, such as miscanthus, is its potential to be an invasive species. The miscanthus variety being evaluated in this study as a feedstock for biofuels is the sterile hybrid genotype *Miscanthus* × *giganteus* that has been studied extensively through field trials in several European countries. *Miscanthus x giganteus* is a cross between two species and has three sets of chromosomes instead of the normal two. This prevents the normal pairing of chromosomes needed to form fertile pollen and ovules and makes it sterile. The majority of growth for switchgrass occurs during June to August while miscanthus biomass accumulation normally achieves the maximum potential between August and October.

Switchgrass stands can have a life-span of 15-20 years in a native state, but in cultivated conditions the U.S. Department of Energy estimates stand-life at 10 years.[9] A ten-year lifetime is also commonly assumed for analyzing the costs of switchgrass production (see Brechbill, Tyner and Ileleji 2008; Duffy 2007; Mooney et al. 2009; Perrin et al. 2008; Qin et al. 2006). Field experiments provide evidence that miscanthus can be productive for 14-18 years in Europe (Christian, Riche and Yates 2008; Clifton-Brown, Brewer and Jones 2007; Lewandowski et al. 2003). In the U.S, more than 20 year-old of miscanthus stands have been observed in experimental fields in Illinois (Heaton, Dohleman and Long 2008). This study assumes a life-span of 10 years for switchgrass and 15 years for miscanthus and examines the sensitivity of model results to a shorter life-span of 10 years for miscanthus.

5.1.1 Yields of Perennial Grasses

In the absence of long term observed yields for switchgrass and miscanthus, this study uses a crop productivity model MISCANMOD to simulate the yields of miscanthus and Cave-in-Rock switchgrass. The Cave-in-Rock switchgrass cultivar studied here is an upland variety that is originated in Southern Illinois with good potential in the northern states of the U.S. and more cold tolerant and suited for the upper Midwest (Lemus and Parrish 2009; Lewandowski et al. 2003). The MISCANMOD estimates the yields of miscanthus and Cave-in-Rock switchgrass using GIS data on climate, soil moisture, solar radiation and growing degree days as model inputs, as described in Jain et al. (2010). Low land of switchgrass, Alamo, grows up to 12 feet tall and is typically found on heavy soils in bottomland sites. Alamo switchgrass is a robust lowland variety of switchgrass most suited to the southern US (Lemus and Parrish 2009). A review of literature shows that annual yield of lowland variety of switchgrass ranges between11-16 metric ton of dry matter per hectare (DMT ha^{-1}) (Lemus and Parrish 2009) and is about 50% higher than that of the upland variety. In the absence of county specific estimates of yields for the lowland variety of switchgrass, we increase switchgrass yields from MISCANMOD by 50% for all regions other than the upper Midwest to account for higher yields of the lowland varieties.

Figure 5.1shows the variability in peak biomass yields for miscanthus and upland and lowland varieties of switchgrass in the U.S. On a per hectare basis, the MISCANMOD model results suggest that the peak biomass yield of miscanthus is about three times the yield of the upland variety of switchgrass and twice the yield of the lowland variety of switchgrass. The simulated yields show that yields of bioenergy crops vary from north to south and from west to east in the U.S. Atlantic states Kentucky, Tennessee, Virginia and North Carolina show high yields for miscanthus and switchgrass with western mountain states Montana, Wyoming, Idaho, Washington, California and Arizona being the regions where estimated yields for bioenergy crops are low due to insufficient soil moisture. In general, southern states, such as Georgia, Alabama and Mississippi, have higher yields for miscanthus and switchgrass than northern states Minnesota and Michigan’s Upper Peninsula. However, northern plain states North Dakota and South Dakota show strong yields for miscanthus while average yields for miscanthus in western and central Texas are close to zero. In addition, yields estimates for switchgrass show that central and northern Texas shows good performance in switchgrass production, with average CRD-level production being 3.1MT ha^{-1} for much of this region. The corn-belt states Illinois, Iowa, Indiana, and Kansas also have high productivity for these bioenergy crops based on the model estimation.

As shown in Table 5.1, the average delivered yield of miscanthus is the highest in the Atlantic states at 31.6 DMT ha^{-1} followed by the South at 30.2 DMT ha^{-1}, Midwest at 23.8 DMT ha^{-1} and the Plains at 19.8 DMT ha^{-1}. Corresponding estimates for average switchgrass yield of the lowland variety are 16.4, 15.2, 10.7, 11 DMT ha^{-1}, respectively.[10]

5.1.2 Production Costs of Bioenergy Crops

Costs of production of miscanthus and switchgrass are developed for each year of their lifetime for each CRD and include the costs of (i) inputs including fertilizer, seed and chemicals; (ii) machinery required for establishment and harvest of bioenergy crops; (iii) storage and transportation, and (iv) opportunity costs of land. The costs of labor, building repair and depreciation, and overhead (such as farm insurance and utilities) are excluded from the costs of production since they are likely to be the same for all crops and would not affect the relative profitability of crops.

Costs of bioenergy crops in the first year differ from those in subsequent years because it involves costs of seeding and land preparation to establish the crops. Existing studies vary in their assumptions about input requirements, pre-harvesing, harvesting and storage costs of bioenergy crops. This study constructs low cost and high cost scenarios for the production of the bioenergy crops, and the simulation model will test the sensitivity of model results to these assumptions. The low cost scenario considers a low fertilizer application rate, low replanting probability, high second-year yield, low harvest loss and low harvesting costs while the high cost scenario considers the opposite scenario of production. These are described in Jain et al. (2010).

Fertilizer, Seed and Chemical Costs: The agronomic assumptions about dry delivered biomass yields, reseeding rates and input application rates are based on information provided in Jain et al. (2010) and Khanna, Dhungana and Clifton-Brown (2008). The production of miscanthus and switchgrass requires inputs of nitrogen (N), phosphorus (P), potassium (K), calcium, chemicals and seed. The applications of these inputs are expected to be age-specific and vary across locations due to the perennial nature of these crops and heterogeneity in land quality. Jain et al. (2010) assume no nitrogen is applied to switchgrass in the first year to prevent weeds and 56 and 140 kg N fertilizer ha^{-1} in liquid form is applied annually thereafter in the low and high cost scenarios. Application rates of P and K in the first year are assumed to be 33.7 kg of P and 44.9 kg of K ha^{-1}(Duffy and Nanhou 2001; Khanna, Dhungana and Clifton-Brown 2008). In the subsequent years, P and K application rates range between 0.42–0.97 kg DMT^{-1} for P and 9.47–11.40 kg DMT^{-1} for K (Duffy and Nanhou 2001), and P and K are assumed to be applied at the lower bound of the above range in the low cost scenario and at the higher bound of the range in the high cost scenario. Lime is only applied in the first year in the high cost scenario with an application rate of 6.7 t ha^{-1}. Herbicide is required in the first 2 years to combat weeds and applied at the rate of 3.5 liter ha^{-1} of Atrazine and 1.75 liter ha^{-1}of 2,4-D but no Atrazine application is assumed in the second year in the low cost case (Duffy and Nanhou 2002). Seed application rates for switchgrass range between 6.5-11 kg ha^{-1} while a 15-50% probability of reseeding is assume in the second year (see Table 1 of Khanna, Dhungana and Clifton-Brown 2008). Switchgrass yield in the first year is assumed to range between 30%-100% of peak biomass yield at harvest in the low cost and high cost scenarios while in the following year it is between 67%-100% of peak biomass yield. The peak biomass yield can be achieved in year 3 and onwards.

In the case of miscanthus, the application of nitrogen is assumed to be 30 kg of N ha^{-1} in year 1 for rhizome development and 25 kg of N ha^{-1} is applied subsequently for the low cost case while for the high cost case the rates are 60 kg of N ha^{-1} in year 1 and 50 kg of N ha^{-1} thereafter (Khanna, Dhungana and Clifton-Brown 2008). P and K application rates are assumed to be 7 and 100 kg ha^{-1}, respectively, starting in the first year and onwards in both low and high cost cases. Lime is only applied in the first year, and ranges between 2.3–4.5 t ha^{-1} in the low and high cost scenarios. The same amount of herbicides per hectare for miscanthus as for switchgrass is applied only in the first year, and we assume no herbicide application in subsequent years (DEFRA 2001). Cost per propagule is assumed to be $0.25 in 2007 prices which leads to a cost of $2471 ha^{-1}. We assume miscanthus harvest starts in the second year with a 40%-50% of peak yield in the low cost and high cost scenarios.

In the second year, we assume that there is a possibility that reseeding/replanting will be needed for bioenergy crops to replace plants that do not survive in their first year. Reseeding rates for miscanthus are assumed to be the same as for switchgrass that are 15% and 50% in the low and high cost cases, respectively. State-level fertilizer prices in 2007 prices reported in Table 5.2 are obtained from state extension services for all states considered here to compute fertilizer costs.

Machinery Costs: The establishment of switchgrass production involves using a tandem disk, a harrow, an airflow planter to spread seeds and phosphorus and potassium fertilizer and a self-propelled sprayer to spray the herbicide and spread liquid nitrogen fertilizer. In the second year, machinery costs for reseeding are assumed to be proportionate to those in the first year while annual maintenance and harvesting are needed on the planted land without reseeding. The establishment costs for miscanthus include costs on a chisel plow, harrow, equipment to apply fertilizer and spray herbicides and a semi-automatic potato planter. Assumption underlying machinery uses and estimated costs for the low cost and high cost scenarios are described in Khanna, Dhungana and Clifton-Brown (2008), and shown in Table 5.3 and Table 5.4. All costs are converted to 2007 prices using the Gross Domestic Product Deflator Index[11].

Harvesting of switchgrass and miscanthus is assumed to be done in one single pass and includes mowing, raking, baling and staging/loading. The harvest of switchgrass is in the early winter after the first frost while the harvest of miscanthus is expected to occur between December and March. We assume a 20% yield loss compared to peak levels of yields for miscanthus and switchgrass in the low cost scenario while a 40% yield loss is assumed for the harvest of miscanthus in the high cost scenario as reported in Khanna, Dhungana and Clifton-Brown (2008). Costs of mowing and raking for miscanthus and switchgrass are assumed to be constant per hectare based on current estimates of the costs of mowing and raking for hay for each state, and obtained from state extension services. Baling costs for bioenergy crops are also estimated based on the costs of baling hay from the estimates in state extension services. In the low cost scenario, some portions of the baling costs are fixed per hectare irrespective of biomass yield while the other portions vary with yields. In the high cost scenario, the baling cost is assumed to vary with crop yields. Staging/loading cost is assumed to be \$2.75 per bale (431 kg) as reported in Khanna, Dhungana and Clifton-Brown (2008). Harvesting costs at state level in 2007 prices are summarized in Table 5.5.

Storage and Transportation: Baled miscanthus and switchgrass are assumed to be stored outside on crushed rock on reusable tarp at a cost of \$3.22 DMT^{-1} as reported in Brummer et al.

(2000). Storage is assumed to result in 7% loss in yields and to reduce the moisture content of miscanthus bales by 15% through natural ventilation and without any additional drying costs. Transportation of biomass is assumed to have a fixed cost of \$4.39 $\text{DMT}^{-1}$and a variable cost of \$0.12 $\text{DMT}^{-1}\text{km}^{-1}$ by Searcy et al. (2007) with a one-way distance of 50 kilometers from farm gate to refinery.

Opportunity Costs of Land: Opportunity costs of land are determined endogenously in the simulation model, and expected to differ across regions since they are the forgone profits from the most profitable alternative use of land that is converted from that use to a bioenergy crop. It is measured by the difference between the per-hectare revenues from the most profitable crop production practice (such as crop rotation and tillage) and associated production costs. The opportunity costs of cropland are expected to account for a large part of the total cost of production of miscanthus and switchgrass, especially in the regions where opportunity costs of land are high and yields of bioenergy crops are low.

Experience in Europe and the U.S. suggests that miscanthus and switchgrass can be productive over a wide geographic range in temperate regions, including marginal land such as idle cropland and cropland pasture[12]. Land conversion costs should be considered as parts of production costs of bioenergy crops if they are planted on marginal lands. Land conversion costs generally include costs for land clearing, wind rowing and burning, and any necessary activities for seedbed preparation of bioenery crop production. In the absence of empirical data, we consider land conversion costs to be the returns to land from the least profitable crop production practice in each CRD. Land conversion costs are also endogenously determined in the simulation model. To illustrate spatial heterogeneity in the production costs of bioenergy crops on marginal lands, we use data on crop yields and associated crop production costs in 2007 prices to compute the conversion costs of marginal lands for each CRD.

Costs of Bioenergy Crops in the U.S: In this study, production of bioenergy crops is limited to the rainfed regions which include the Plains, Midwest, South, and Atlantic, and exclude Western mountain states such as Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming from planting bioenergy crops due to their relatively low yields under rainfed conditions. We calculate CRD-level annualized costs per hectare for miscanthus and the upland and lowland varieties of switchgrass. In the low cost scenario, the cost estimates for the upland variety of switchgrass on regular cropland including opportunity costs of cropland range from \$71 to \$146 DMT^{-1} across the U.S. The costs of the lowland variety of switchgrass are smaller, ranging from \$54 to \$111 DMT^{-1} because of higher yields. The costs of miscanthus vary more widely between \$41 and \$156 DMT^{-1}. In the high cost scenario, cost estimates for bioenergy crops are significantly higher than the low cost scenario. The costs range between \$99 and \$190 DMT^{-1} for the upland variety of switchgrass and between \$73 and \$140 DMT^{-1} for the lowland variety of switchgrass, respectively. The costs of miscanthus in the high cost scenario are also higher between \$65 and \$235 DMT^{-1}.

In the low cost scenario, the costs of production of switchgrass and miscanthus on marginal lands are presented in Figure 5.2. These costs are significantly lower than those on regular cropland. That is because bioenergy crops on marginal lands do not create competition for land with food crops, and it only involves one-time conversion cost. The costs of the upland variety of switchgrass range from \$38 to \$58 DMT^{-1}while the lowland variety of swithchgrass has lower costs ranging from \$32 to \$49 DMT^{-1}. The costs for the production of miscanthus are also considerably low relative to that on regular cropland changing from \$31 to \$70 DMT^{-1}.

The spatial distribution of CRD-level production costs of bioenergy crops shows that in general the upland variety of switchgrass is more costly to produce than miscanthus but not for the CRDs in northern Midwestern states (Minnesota and Wisconsin) and southern states (Texas and Louisiana) that have relatively high switchgrass yields. The lowland variety of switchgrass has cost advantages over miscanthus in North Dakota, Missouri, Florida, North Carolina and Pennsylvania due to its higher yields. Texas has the lowest average cost of the lowland variety of switchgrass production (\$50 DMT^{-1}) because of its higher yield. Cost comparison of bioenerngy crops suggests that there is considerable spatial variation in the costs of cellulosic feedstocks in the U.S. and that the mix of bioenergy crops will differ across geographic locations.

5.2 Conventional Crop 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) under dryland and irrigated land. 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 rates and elasticities used in the model and more details of the econometric estimation methods can be found in Huang and Khanna (2010). Some crops are grown in rotation with each other to increase soil productivity and reduce the need for fertilizers. We adjust crop yields per hectare based on crop rotations for each CRD. We obtain 15 crop rotation possibilities for each region of the U.S. from USDA/ERS (1997), including corn-soybean rotation, continuous corn rotation, fallow-wheat rotation and continuous rotations for other crops. In Midwestern states where a corn-soybean rotation is the dominant rotation practice, we assume observed corn yields to be those under a corn-soybean rotation. Corn yields per hectare under a continuous corn rotation are assumed to be 12% lower than under a corn-soybean rotation. The fallow-wheat rotation is primarily used to conserve soil moisture over a 2-year period for 1 year production, which leads to a reduction in wheat yields by 50% in this rotation. The fallow-wheat rotation is widely used in the Northern wheat-growing region (such as Washing, Oregon, Idaho, Montana and Colorado) and in parts of the Northern Plains states (such as North Dakota, South Dakota, Nebraska and Kansas). Some counties in Minnesota and Texas also use the fallow-wheat rotation.[13]

Corn stover and wheat straw yields for each CRD are obtained based on a 1:1 grain-to-residue ratio of dry matter of crop grain to dry matter of crop residues and 15% moisture content in the grain reported in Sheehan et al. (2003), Wilcke and Wyatt (2002) and Graham, Nelson and Sheehan (2007). 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 till or conventional tillage is used. Corn stover yield ranges from 0.16-5.07 DMT ha^{-1} under no-till while wheat straw yield ranges from 0.34 to 4.38 DMT ha^{-1} in the U.S. Ethanol yield from corn grain is 417.3 liters of denatured ethanol per metric ton of corn while cellulosic biofuel yield from an nth-generation stand alone plant is estimated as 330.5 liters per metric ton of dry matter of biomass (Wallace et al. 2005).

5.3 Production Costs of Conventional Crops

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. Crop budgets vary by rotation, tillage and irrigation choices. The costs of crop production include costs of inputs such as fertilizer, chemicals and seeds, costs of drying and storage, costs on machinery and fuels and costs of crop insurance. We also include interest payments based on a 7% interest rate on all variable input costs. 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. We determine the cost of production of corn silage by estimating the foregone revenue per hectare by growing corn silage instead of corn, the additional cost of fertilizer replacement that is needed for corn silage, and harvesting costs as reported in FBFM[14].

Application rates for nitrogen, phosphorous and potassium and seeds for row crops and alfalfa vary with crop yields, and differ across CRDs. Other costs of producing crops are assumed to be fixed irrespective of crop yields per hectare but differ across states. In addition, costs of fertilizer, chemicals and machinery under conventional tillage differ from those under conservation tillage. Compiled crop budgets show that machinery costs under conservation tillage are likely to be lower than those under conventional tillage for most crop production. However, fertilizer costs under conservation tillage are higher than under conventional tillage.

The costs of collecting 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. In addition, the collection of crop residues involves the costs of harvesting stover and staw (i.e., mowing, raking, baling, staging and storage) that are estimated based on the state-specific crop budgets on hay alfalfa harvesting (Jain et al. 2009). Costs of collecting corn stover and wheat straw are shown in Figure 5.3. In general, the costs of production of crop residues are higher than those of bioenergy crops grown on marginal lands, except for corn stover in Plain states, such as North Dakota, South Dakota and Nebraska where corn yields are high due to irrigation. High wheat yields in western mountain states (such as in Oregon, Idaho and Washington), can make wheat straw competitive with bioenergy crops in the production of cellulosic biofuels.

5.4 Land Availability

Five types of land (cropland, idle cropland, cropland pasture, pasture land and forestland pasture) are specified for each CRD. We obtain CRD-specific planted acres for 15 row crops for the period 1977 to 2007 from USDA/NASS (2009). We use this to construct the cropland available in 2007 that is 123 M ha for 280 CRDs considered here, and to obtain the historical and synthetic mixes of row crops. Cropland availability in each CRD is assumed to change in response to crop prices. 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).

Data on idle cropland, cropland pasture, pasture and forestland pasture for each CRD are obtained from USDA/NASS (2009). Idle cropland includes land use category for cropland in rotations for soil improvement, and cropland on which no crops were planted for various physical and economic reasons. The estimates of idle land include land enrolled in the Conservation Reserve Program (CRP), which could be an additional source of land available for energy crops. Land in this program is farmland that is converted to trees, grass, and areas for wildlife cover. Environmental benefits of this land include the creation of wildlife habitat, increasing soil productivity, reducing soil erosion and improving ground and surface water quality. We distinguish between idle cropland and land enrolled in Federal Conservation Reserve Program (CRP) in the simulation model. We also consider the sensitivity of our results to a constraint on the use of CRP land for bioenergy crop production. Cropland pasture is considered as a long-term crop rotation between crops and pasture at varying intervals. It includes land that was used for pasture before crops reach maturity and some land used for pasture that could have been cropped without additional improvement. Figure 5.3 shows the allocation of marginal lands in the United States. As of 200, total availability of idle cropland is 15 M ha while cropland pasture is 13 M ha.

Pasture land consists of land with shrub, brush, all tame and native grasses, legumes and other forage while forestland pasture is stocked by trees of any size and includes a certain percentage of tree cover. Pasture land and forestland pasture are primarily for grazing uses with the former being 155 M ha and the latter estimated as 10.5 M ha in 2007. Costs of land conversion from marginal lands to regular cropland include costs for land clearing, wind rowing, burning and any necessary activities. Land conversion costs differ across the U.S. and are assumed to be the difference between revenues per hectare from the least profitable land practices and associated production costs.

5.5 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 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).

Specifically, inputs for feedstock production include fertilizer, herbicides and insecticides. Energy used in the production of crops and biofuel feedstock includes the direct consumption of gasoline, diesel, liquefied petroleum gas, and electricity, and the indirect consumption of energy embodied in farm equipment such as tractors and plows. Similarly, CO_2e generated during the biorefinery phase accounts for the energy used to convert the feedstock to fuel and the energy embodied in buildings and equipment in the biorefinery. CO_2e is obtained by aggregating the CO_2 emissions from the energy used and the GHG emissions induced from the use of the inputs such as nitrogen and lime. For more details regarding the assumptions and parameters used in our life cycle analysis for biofuel feedstock production, see Dhungana (2007); for biofuel conversion, see Argonne National Laboratory (2009). CO_2e from corn stover ethanol is estimated using an incremental emissions approach as in Wu, Wang and Huo (2006). Specifically, life cycle emissions arising from stover harvesting and additional chemical application as a result of stover removal are evaluated. As shown in Table 5.6, ethanol produced from miscanthus generates the least GHG emissions at 0.09 kg liter^{-1} in the U.S, followed by upland variety of switchgrass at 0.26 kg liter^{-1}, lowland variety of switchgrass at 0.37 kg liter^{-1}, wheat straw at 0.39 kg liter^{-1}, stover at 0.65 kg liter^{-1}and corn at 1.11kg liter^{-1}. It also shows regional variations in GHG emissions for biofuels produced from alternative feedstocks; ethanol produced from miscanthus in Atlantic states is the least carbon intensive biofuel with 0.06 kg liter^{-1}while this region also produces the most carbon intensive corn ethanol at 1.36 kg liter^{-1}.

5.6 Crop and Livestock Sector

In the livestock sector we consider demands for several types of meat (chicken, turkey, lamb, beef and pork), wool, dairy and eggs. The demand functions are calibrated using the observed quantities consumed and prices and demand elasticities. The latter are obtained from Adams et al. (2005). The supply of livestock (chicken, turkey, lamb and pork) is constrained by their historical numbers at the national level. The supply of beef is restricted by the number of cattle which in turn depends on the amount of grazing land available at regional level. The historical livestock data at the national level and production of meat, dairy and eggs for 2003-2007 are used to obtain the average livestock productivity. The CRD level availabilities of pasture, forest and range lands in 2007 that can be used for grazing cattle are obtained from ERS/NASS[15]. The data on grazing land requirements for cattle, nutrition requirements (in terms of protein and grain) for each livestock category, and production and processing costs are obtained from Adams et al. (2005). We use the nutrient content of feed crops, soymeal and DDGS to find the least cost feed rations for each type of livestock. The price of DDGS is determined by the lagged prices of corn and soymeal using the relationship estimated by Ellinger (2008). To prevent unrealistic feed mixes consumed by livestock we constrain the consumption of different types of feed based on the historically observed levels obtained from USDA/NASS (2009).

The crops sector consists of markets for primary and processed commodities. The demands for primary commodities, such as, corn and soybeans are determined in part by the demands for processed commodities obtained from them and by other uses (such as seed). The conversion rates from primary crop commodities to processed commodities are obtained from USDA/NASS (2009). The conversion costs are obtained from Adams et al. (2005) and inflated to 2007 prices using the respective GDP deflator. We use two-year (2006-2007) average prices, consumption, exports and imports of crop and livestock commodities to calibrate the domestic demand, export demand and import supply functions for all commodities[16]. The data on prices, consumption, exports and imports are obtained from ERS/USDA. Elasticities are assembled from a number of sources including FASOM, USDA and exiting literature. Domestic demands, export demands and import supplies are shifted upward over time at exogenously specified rates, and they are listed in Table 5.7. We obtain projected amount of crop and livestock commodities for domestic consumption, exports and imports for 2010 and 2020 from FAPRI[17]. Annual growth rates for commodities are calculated by using the one-tenth of total percentage growth rates between 2010 and 2020. This can be written as: $\text{annual growth rate}=\frac{1}{10}.\frac{\text{demand in 2020}}{\text{demand in 2010}}$.

5.7 Fuel Sector

In the fuel sector, we consider a linear demand function for miles. The price elasticity of miles demand is assumed to be -0.2, and we assume demand for miles shifts out 1% each year after the base year[18]. The elasticity of substitution between gasoline and ethanol is 3.95 (Hertel, Tyner and Birur 2008). For the supply of gasoline, we consier two gasoline supply curves to distinguish domestic gasoline supply and gasoline supply from the rest of the world. The short-run supply of domestic gasoline is assumed to be linear with a slope of 0.9 (Greene and Tishchishyna 2000) while the short-run gasoline supply to the U.S. from the rest of the world is assumed to have a constant elasticity form with a price-elasticity of 2[19].

To calibrate the demand function of miles, production function of miles and supply functions of gasoline, data on consumption of kilometers and fuel consumption and fuel prices in 2007 are assembled from several sources. The Federal Highway Administration (FHWA) reports that total vehicle-miles traveled in 2007 were 5107 B kilometers. The Energy Information

Administration (EIA) reports that the consumption of gasoline and ethanol are 519.4 B liters and 23.4 B liters, respectively, in the U.S. in 2007. The EIA reports that average retail price of gasoline that year was \$0.72 per liter. We calculate the retail price of ethanol as the wholesale rack price plus \$0.10 per liter fuel taxes and a \$0.05 per liter markup minus \$0.13 per liter subsidy, yielding \$0.61 per liter in 2007[20].

We assume linear supply functions for ethanol imports from Brazil and CBI countries, and use two-year (2006-2007) average prices and imports of ethanol imports to calibrate the ethanol import supply functions. Data on ethanol imports including excess supply elasticities, prices of sugarcane ethanol in Brazil and CBI countries, life-cycle GHG emissions of sugarcane ethanol are obtained from several sources. The excess supply elasticities of imported ethanol from Brail and CBI counties are assumed to be 2.7 as reported in de Gorter and Just (2008). We calculate the sugarcane ethanol prices in Brazil and CBI countries as the U.S. retail price minus \$0.02 per liter transportation cost, the fuel tax and tariff, and plus subsidy, yielding \$0.49 and \$0.62 per liter, respectively.[21] The carbon emissions of sugarcane ethanol at U.S. ports are estimated to be 0.55kg per liter (Lasco et al. 2009).

The cost of conversion of corn grain to ethanol is estimated as \$0.18 per 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. We assume b for corn ethanol is equal to -0.20 (Hettinga et al. 2009) and calibrate C_0 using data on the processing cost and cumulative corn ethanol production in 2007. To calibrate the function for cellulosic ethanol we assume C_{cum} in 2022 is $0.24 per liter (EPA 2009) and use the production quantities specified in the RFS to obtain a value for b of -0.05.[22] The processing costs of corn ethanol and cellulosic ethanol during 2007-2022 period are shown in Figure 5.3. We assume the feedstock and refinery costs of sugarcane ethanol in Brazil and CBI countries follow the similar declining functions of cumulative production. We assume b for sugarcane ethanol is -0.32 (van den Wall Bake et al. 2009). Parameter C_0 is calibrated using data on the feedstock and refinery costs of sugarcane ethanol and cumulative sugarcane ethanol production in 2007. We also assume that the growth rate of sugarcane ethanol production to be constant and equal to 8% (van den Wall Bake et al. 2009), and exogenously compute the feedstock and refinery costs of sugarcane ethanol for 2007-2022.

Figures and Tables

Table 5.1: Delivered Yields of Miscanthus and Switchgrass (Metric Ton Dry Matter ha^{-1})

Region	Miscanthus		Upland Variety of Switchgrass		Lowland Variety of Switchgrass	
	Average	Range	Average	Range	Average	Range
Atlantic States	31.6	4.4 - 49.3	10.9	7.9 – 12.8	16.4	11.8 – 19.2
Midwestern States*	23.8	2.3 – 38.3	9.5	7.0 - 12.4	10.2	7.0 – 17.7
Plain States	19.8	0.1 – 38.1	7.3	0.4 – 10.8	11.0	0.7 – 16.2
Southern States	30.2	6.2 – 45.0	10.1	7.7 - 11.7	15.2	11.5 - 17.6
Western States	12.4	1.3 – 23.8	4.7	0.1 – 10.6	7.0	0.1 – 15.9

*In Midwestern states, only Missouri is suitable for the upland variety of swithchgrass.

Table 5.2: Fertilizer Costs in 2007 Prices

State	Nitrogen ($/kg)	Phosphorus ($/kg)	Potassium ($/kg)	Lime ($/MT)
Alabama	1.10	0.81	0.48	25.00
Arkansas	0.51	0.51	0.51	36.00
Florida	0.95	0.73	0.51	33.00
Georgia	0.95	0.68	0.51	28.00
Kansas	0.77	0.66	0.57	20.00
Kentucky	0.88	0.90	0.53	14.50
Louisiana	0.66	0.57	0.33	14.50
Maryland	0.70	1.01	1.41	43.27
Mississippi	0.90	0.73	0.51	25.00
Nebraska	0.99	0.51	0.33	20.00
New Jersey	0.77	0.81	0.81	32.82
New York	0.77	0.81	0.81	32.82
North Carolina	0.86	0.77	0.64	42.50
North Dakota	0.95	0.86	0.62	20.00
Oklahoma	0.77	1.10	0.48	20.00
Pennsylvania	0.77	0.81	0.81	32.82
South Carolina	1.23	0.79	0.64	52.50
South Dakota	0.77	0.51	0.44	20.00
Tennessee	0.68	0.70	0.48	23.00
Texas	0.44	0.90	0.77	14.50
Virginia	0.84	0.70	0.57	32.50
West Virginia	0.99	0.99	0.44	32.5
Illinois	0.77	0.66	0.59	20.00
Indiana	0.88	0.88	0.51	13.76
Iowa	0.68	0.81	0.51	21.00
Michigan	1.08	0.64	0.55	23.00
Minnesota	0.77	1.17	0.99	20.00
Missouri	0.57	0.51	0.35	11.64
Ohio	0.77	0.70	0.46	22.70
Wisconsin	0.40	0.44	0.31	18.00

Table 5.3: Pre-harvesting Costs for Miscanthus in Low Cost and High Cost Scenarios

	Year 1	*Year 2*	*Year 3*
Chisel plowing ($/ha)	33.1	5.0-16.6	0
Harrowing ($/ha)	13.9	2.1-7.0	0
Potato planter ($/ha)	77.3	11.6-38.6	0
Fertilizer spreader ($/ha)	7.9	7.9	7.9
Spraying chemicals ($/ha)	12.7	1.9-6.4	0

Table 5.4: Pre-harvesting Costs for the Lowland Variety of Switchgrass in Low Cost and High Cost Scenarios

	Year 1	*Year 2*	*Year 3*
Disking ($/ha)	23.4	0	0
Harrowing ($/ha)	13.9	0	0
Airflow spreader ($/ha)	7.9	7.9	7.9
Spraying ($/ha)	12.7	1.9-12.7	0-12.7

Table 5.5: Harvesting Costs in 2007 Prices

State	Mowing ($/ha)	Raking ($/ha)	Baling($/DMT) – High Cost	Baling($/DMT) – Low Cost	
				Fixed cost ($/ha)	Variable cost ($/DMT)
Alabama	36.72	11.61	18.02	28.02	6.68
Arkansas	30.10	15.07	13.76	12.78	8.59
Florida	36.72	11.62	18.02	28.02	6.68
Georgia	36.72	11.62	18.02	28.02	6.68
Kansas	24.73	8.43	17.23	32.77	3.96
Kentucky	24.78	13.34	17.04	25.11	6.88
Louisiana	30.10	15.02	13.76	12.78	8.59
Maryland	34.20	22.04	19.89	27.75	8.66
Mississippi	30.10	15.02	13.76	12.78	8.59
Nebraska	15.34	8.43	11.81	21.50	3.11
New Jersey	34.20	22.04	19.89	27.75	8.66
New York	34.20	22.04	19.89	27.75	8.66
North Carolina	45.61	10.87	14.32	19.99	6.23
North Dakota	15.34	8.43	11.81	21.50	3.11
Oklahoma	20.39	7.78	16.00	30.44	3.68
Pennsylvania	34.20	22.04	19.89	27.75	8.66
South Carolina	45.61	10.87	14.32	19.99	6.23
South Dakota	15.34	8.43	11.81	21.50	3.11
Tennessee	30.10	15.02	13.76	12.78	8.59
Texas	20.39	7.78	16.00	30.44	3.68
Virginia	34.20	22.04	19.89	27.75	8.66
West Virginia	34.20	22.04	19.89	27.75	8.66
Illinois	35.09	11.12	19.07	35.34	4.77
Indiana	24.78	13.34	17.04	25.11	6.88
Iowa	35.09	11.12	19.07	35.34	4.77
Michigan	35.09	11.12	19.07	35.34	4.77
Minnesota	35.09	11.12	19.07	35.34	4.77
Missouri	35.09	11.12	19.07	35.34	4.77
Ohio	35.09	11.12	19.07	35.34	4.77
Wisconsin	35.09	11.12	19.07	35.34	4.77

Table 5.6: GHG Emissions from Alternative Feedstocks for Biofuel Production (kg/liter)

Region	**Corn**	**Stover**	**Straw**	**Lowland Switchgrass**	**Upland Switchgrass**	**Miscanthus**
Midwest	1.16	0.19	0.29	0.37	0.36	0.09
South	1.16	0.23	0.39	0.34	0.21	0.07
Plains	0.96	0.33	0.39	0.45	0.29	0.13
Atlantic	1.36	0.39	0.43	0.31	0.20	0.06
West	0.91	2.10	0.45			
U.S.	1.11	0.65	0.39	0.37	0.26	0.09

Table 5.7: Domestic Demand, Export Demand, Import Supply Elasticities[1]

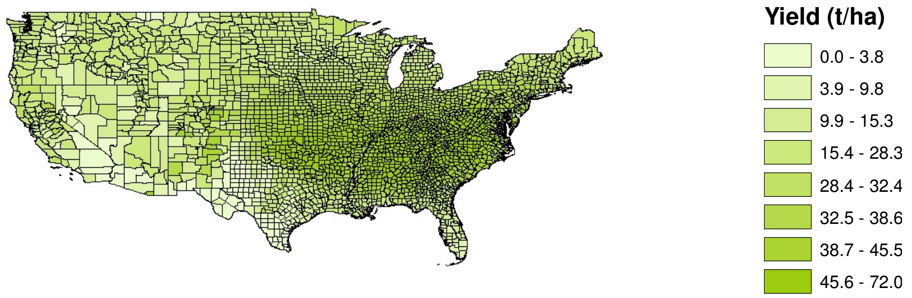
Commodity	Uses	Shift (%)[2]	Elasticities	Sources
Barley	Domestic	0.0	-0.3	USDA/ERS (2009)
	Export	2.0	-0.2	Adams et al. (2005)
Corn	Domestic	0.8	-0.23	Adams et al. (2005)
	Export	2.0	-0.26	Fortenbery and Park (2008)
Cotton	Domestic	-2.0	-0.18	Adams et al. (2005)
	Export	0.3	-0.65	Bredahl et al. (1979)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

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

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

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

(a) Miscanthus



(b) Upland Variety of Switchgrass (c) Lowland Variety of Switchgrass

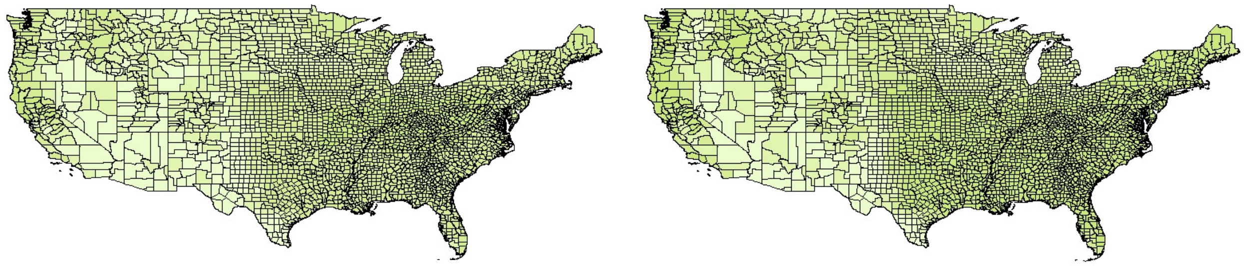
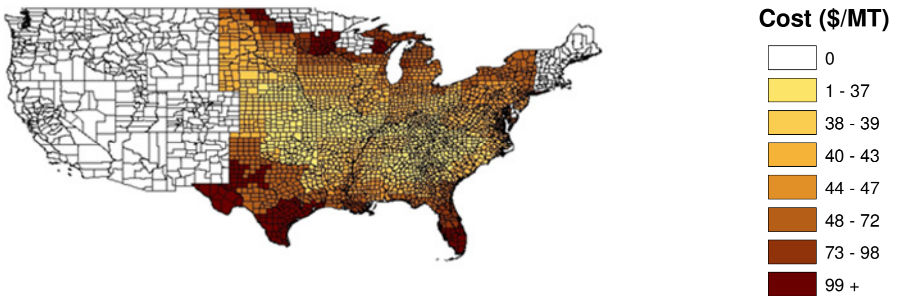


Figure 5.1: Yields of Miscanthus and Switchgrass

(a) Miscanthus



(b) Upland Variety of Switchgrass

(c) Lowland Variety of Switchgrass

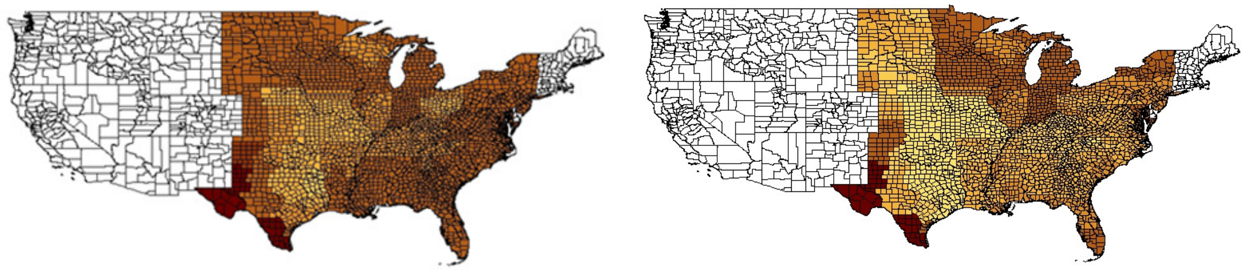
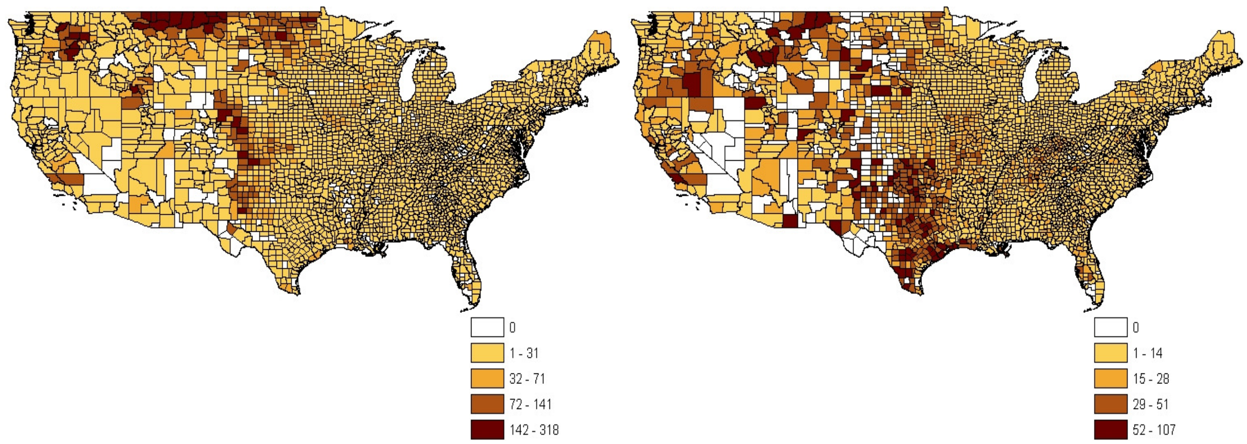


Figure 5.2: Estimated Total Costs of Production of Miscanthus and Switchgrass in 2007 Prices on Marginal Lands



(a) Idle Cropland

(b) Cropland Pasture

Figure 5.3: Marginal Land Availability in 2007 (1000 Acres)

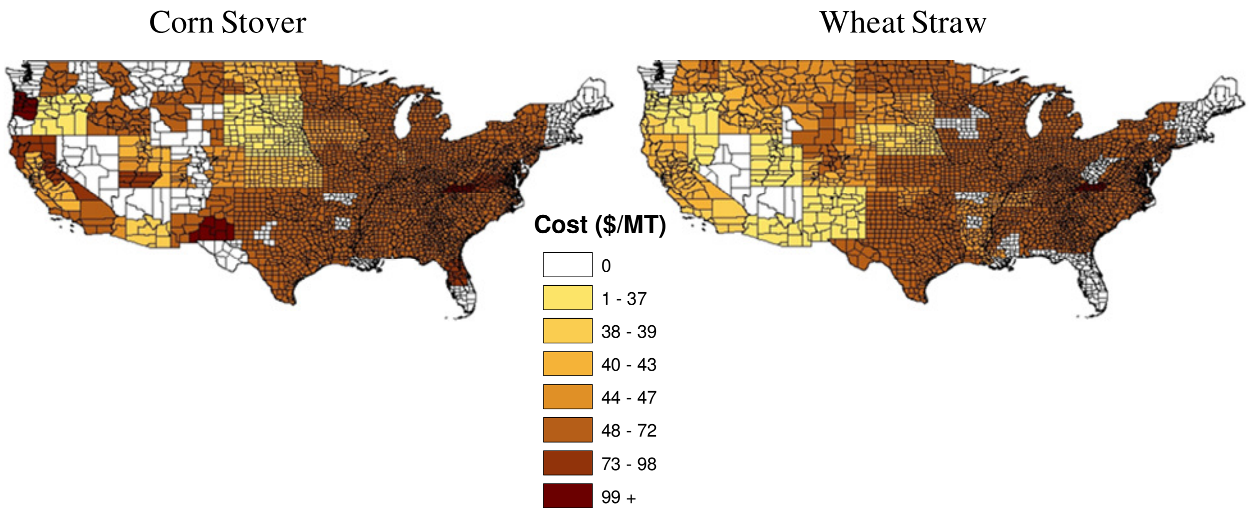


Figure 5.4: Estimated Total Costs of Production of Crop Residues in 2007 Prices

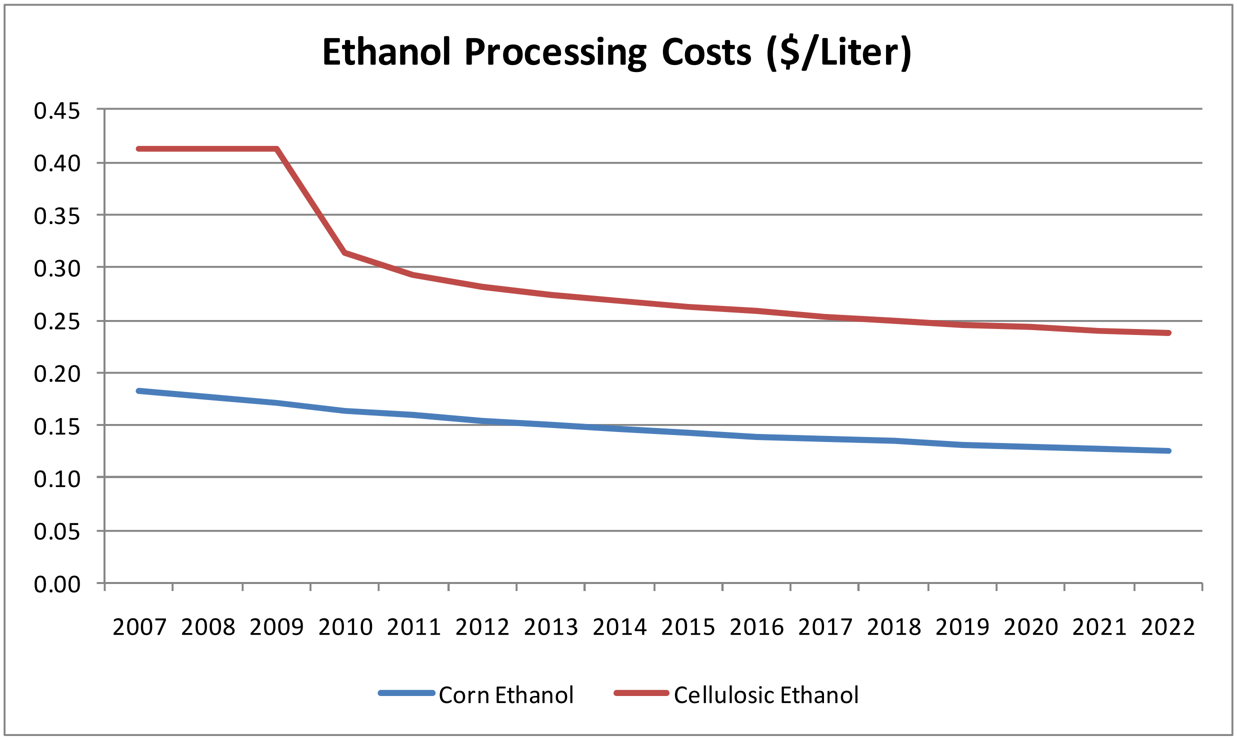


Figure 5.5: Processing Costs of Corn Ethanol and Cellulosic Ethanol Over 2007-2022

Chapter 6: Meeting the Mandate for Biofuels: Implications for Land Use, Greenhouse Gas Emissions and Social Welfare

This chapter uses the simulation model BEPAM developed in chapter 4 to analyze the markets for fuel, biofuel, food/feed crops and livestock for the period 2007-2022. It analyzes the effects of the RFS mandates and biofuel subsidies on cropland allocation among food and fuel crops, food production and food and fuel prices. It also examines the mix of cellulosic feedstocks that are economically viable under alternative policy scenarios. Moreover, we compare the reduction in GHG emissions and welfare costs under biofuel mandates and subsidies to a carbon tax. We report two sets of model results using the upland and lowland (50% higher switchgrass yields) varieties of switchgrass, respectively, to test the robustness of results. We also conduct sensitivity analyses for key parameters that describe market conditions in the fuel sector and parameters that represent technology and production costs of crops in the agricultural sector.

6.1 Effect of Biofuel and Climate Mitigation Policies on the Agricultural and Fuel Sectors

We first validate the simulation model assuming existing fuel taxes and corn ethanol tax credits and compared the model results on land allocation, crop production, biofuel 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 6.1, the differences between model results and the observed land use allocations are typically less than 10% with the exception of sorghum where the deviation in land allocation is 11%. Food prices are generally within 10% of the observed values except for the corn and soybean prices which are 11% and 12% lower than the actual prices in 2007. The fuel prices and fuel consumption are also simulated well, within 5% deviation from the observed values with the exception for ethanol consumption that is 9%. We consider these results as a fairly good sign of the model's validation capability.

We then examine the effects of three 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 volumetric tax credits and compare them to those under a business-as usual (BAU) scenario. The BAU scenario is defined as one without any biofuel 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 \$0.10 per liter, and assume that the demands for crops and VMT increase over time. In the benchmark case we use the parameters defined in chapter 5 for the fuel sector. To examine the effects of different varieties of switchgrass on model results, we present two types of results using upland and lowland varieties of switchgrass, respectively. We also perform a sensitivity analysis using alternative values for the parameters in the fuel sector as well as for various crop production and yield parameters, as discussed below. We considered alternative prices for carbon, but do not report those results for brevity. Results for the benchmark case using the upland variety of switchgrass are presented in Tables 6.2 and 6.3, while results using the lowland variety of switchgrass are presented in Table 6.5 and 6.6.

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

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 3% while ethanol consumption increases by 21% compared to the BAU scenario over the 2007-2022 period. Of the 247 B liters reduction in cumulative gasoline consumption over the 2007-2022, about 89% would come from the reduction in gasoline imports from the rest of the world. This tax would increase demand for ethanol by 69.7 B liters over the 2007-2022 period and it raises the corn price in 2022 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 5% 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 decrease by 0.84 B metric tons (3%) 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 make cellulosic biofuels a viable strategy for GHG mitigation.

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

The biofuel mandate results in a reduction in gasoline consumption over the period of 2007-2022 by 7% and a reduction in gasoline price in 2022 by 8% compared to the BAU levels. The reduction in gasoline supply from the rest of the world would account for 88% of the total reduction in gasoline over the 2007-2022. As a result of the mandate, the volumetric share of ethanol in total fuel consumption increases to 21% in 2022. The cost of cellulosic biofuels is $0.77 per liter, significantly higher than the cost of corn ethanol ($0.69 per liter) and gasoline ($0.72 per liter) in 2022. However, the displacement of gasoline lowers the overall cost of VMT from $0.087 per km to $0.0.086 per km and as a result the VMT increases by 0.3% relative to the BAU scenario in 2022. This market-based feedback effect on gasoline prices tempers the extent to which biofuels replace gasoline. Overall reduction in cumulative GHG emissions is 1.1 B metric tons (4% relative to BAU) and is more than the reduction achieved by the tax of $30 per ton CO_2e.

As shown in Table 6.5, the introduction of the lowland variety of switchgrass would increase the acreage under switchgrass in 2022 from 1.2 M ha using the upland variety of switchgrass to 3.7 M ha while the acreage under miscanthus in 2022 would decrease from 6.5 M ha to 5.2 M ha. The land from which corn stover and wheat straw would be harvested in 2022 decreases by 4% and 39%, respectively, relative to results with the upland variety of switchgrass. Increased switchgrass yields would mitigate the competition for cropland, and as a result land under corn, soybean, wheat and alfalfa slightly increase compared to that using the upland variety of switchgrass. In comparison to the BAU, the mandate leads to a 20% increase in land under corn in 2022 while total cropland increases by about 2% (2.8 M ha). Corn and soybean prices in 2022 are 23% and 21% higher than the BAU.

With higher switchgrass yields, the volumetric share of cellulosic biofuels made from switchgrass in total cellulosic ethanol production would increase from 5% using the upland variety of switchgrass to 21%. Miscanthus is still the primary cellulosic feedstock in meeting the mandate for advanced biofuels, accounting for 72% in total cellulosic ethanol production. The price of cellulosic ethanol in 2022 is $0.92 per liter of biofuel that is higher than the cost of cellulosic ethanol with the upland variety of switchgrass. The effects of adopting the lowland variety of switchgrass on gasoline consumption and price, VMT and GHG emissions are not significantly different with that using the upland variety. In comparison to the BAU, the biofuel mandate results in a reduction in gasoline consumption over the period of 2007-2022 by 7% and a reduction in gasoline price in 2022 by 8%. Cumulative VMT consumption over the 2007-2022 increases by 0.2% relative to the BAU while cumulative GHG emissions decrease by 4%.

Biofuel Mandate and Subsidies: The provision of tax credits for biofuels leads to two significant shifts in the mix of feedstocks used for biofuels. First, it makes cellulosic ethanol competitive with corn ethanol and reduces cumulative corn ethanol production from its upper limit set under the RFS at 802 B liters to 162 B liters. Cumulative cellulosic ethanol production is 2.5 times of that under a mandate alone from 420 B liters to 1059 B liters over the 2007-2022 period. Second, it increases the share of corn stover in cumulative cellulosic biofuels from 4% under a mandate alone to 5% under a mandate with subsidies. The corresponding shares of other cellulosic feedstocks slightly fall. The increase in biofuels produced from miscanthus and switchgrass increases their acreages from 6.5 and 1.2 M ha under a mandate alone to 12.4 and 1.9 M ha. Of the 14.3 M ha under bioenergy crops, only 1.6 M ha under miscanthus is diverted from regular cropland, and 12.7 M ha land is from the conversion of marginal lands. The provision of biofuel subsidies also increases the acreage from which corn stover and wheat straw are harvested in 2022.

The change in the composition of biofuels due to the subsidies affects the total land under crop production and under various row crops. The need for total cropland diminishes by about 5.5 M ha relative to the mandate alone since a larger portion of the mandate is met by high yielding feedstocks. Corn acreage and corn price in 2022 decline by 15% relative to the BAU; 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 \$0.52 per liter for corn ethanol and \$0.50 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 543 B kilometers (0.7%) and gasoline consumption increases by 59 B liters (0.7%) relative to the levels under the mandate alone. The mandate and subsidies scenario results in the displacement of 547 B liters of gasoline (6%) relative to the BAU scenario while increasing the cumulative biofuel production by 894 B liters over the 2007-2022 period. With the energy content of ethanol being about 67% of that of gasoline, the miles per energy equivalent liter remains at about 9.1 kilometers per 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% increase in the cumulative VMT (or an additional 0.8 trillion kilometers) under the mandate and subsidies compared to the BAU over this period. Unlike the theoretical model shows that biofuel subsidies accompanied with the biofuel mandates increase GHG emissions relative to the mandate alone, we find that the biofuel subsidies result in further decline in GHG emissions relative to the mandate alone and relative to the carbon tax. That is because the biofuel subsidies induce a switch away from gasoline and corn ethanol towards cellulosic ethanol. The total GHG emissions would now be decreased by about 6% relative to the BAU scenario over the 2007- 2022 period.

As shown in Table 6.6, with the lowland variety of switchgrass, biofuels produced from switchgrass increase by more than three-fold in comparison to the mandate and subsidy scenario with the upland variety of switchgrass. However, total cellulosic ethanol production decreases by 8% (88 B liters) relative to the mandate and subsidy scenario with the upland variety of switchgrass due to lower yields of switchgrass per hectare relative to miscanthus. Cumulative corn ethanol production is 250 B liters, which is 54% higher than the production of corn ethanol under the mandate plus subsidy scenario with the upland variety of switchgrass.

Higher switchgrass yields also increases the acreage under switchgrass by 116% relative to the mandate and subsidy scenario with the upland variety of switchgrass while miscanthus acreage decreases by 16%. The acreage from which corn stover and wheat straw are harvested also increases relative to the mandate and subsidy scenario with the upland varieties. The change in the composition of biofuels due to the subsidy diminishes the demand for total cropland by about 2.2 M ha relative to the BAU. Corn acreage in 2022 declines by 13% relative to the BAU, and corn price decreases by 10%.

The adoption of lowland variety of switchgrass would marginally increase the consumer price of cellulosic biofuel relative to the mandate and subsidy scenario with the upland variety of switchgrass. Cumulative VMT over the 2007-2022 period increases by 508 B kilometers instead of 580 B under the mandate and subsidy scenario with the upland variety of switchgrass. The total GHG emissions would now be decreased by about 5% relative to the BAU scenario over the 2007- 2022 period due to decreased GHG intensity of the blended fuel. The reduction in GHG emissions achieved here is 0.1 B MT higher than that under the mandate and subsidy scenario with the upland variety of switchgrass due to higher GHG intensity of switchgrass than miscanthus.

6.2 Spatial Distribution of Cellulosic Feedstocks under Biofuel Policies

Aggregate Acreages: Figures 6.1 shows how the production of bioenergy crops changes over time under the RFS only and under the RFS and subsidy scenarios while Figure 6.2 presents the acreage under four cellulosic feedstocks under the RFS mandate and subsidy scenario. To meet the cellulosic biofuel mandates, a mix of feedstocks (corn stover, wheat straw, switchgrass and miscanthus) is used, where the mix differs over time. The production of energy crops increases over time with miscanthus playing a more important role in meeting the cellulosic biofuel target, accounting for 91% and 90% of the total cellulosic ethanol produced for 2007- 2022 under the mandate and the mandate and subsidy scenarios, respectively. The effects of biofuel subsidies have their largest effect on the acreage of miscanthus as shown in Figure 6.1. Under the mandate-only scenario, the miscanthus acreage is 6.5 M ha in 2022, while the biofuel subsidies lead to a much more dramatic increase, 12.4 M ha in 2022.

Figures 6.3 and 6.4 show the land under cellulosic feedstocks over time under the RFS alone and under the RFS and subsidy with the lowland variety of switchgrass. With a higher yield of switchgrass, the land under switchgrass is significantly higher than that with the upland variety, using 3.7 M ha in 2022 under a mandate alone. However, biomass produced from miscanthus is still the major source in meeting the advanced biofuel target under the mandate and the mandate and subsidy scenarios, accounting for 72% and 69% of the total cellulosic ethanol production over the 2007-2022 period. Biofuel subsides significantly increase the acreage under miscanthus that increases from 4.1 M ha under a mandate alone to 10.4 M ha. Land under switchgrass initially increases, but approaches to the level under a mandate alone as the advanced biofuel mandate increases due to its lower yields per hectare relative to miscanthus.

Spatial Distribution: Figure 6.5 and 6.6 show the spatial distribution of cellulosic feedstocks under the RFS only and under the RFS and subsidy scenarios. Corn stover comes primarily from the plain states Nebraska, South Dakotas and Kansas. Wheat straw is collected mainly in the central and northern plains and western mountain states (Kansas, Nebraska, North and South Dakotas, Montana, Idaho and Washington). Production of miscanthus is more concentrated in the Great Plains (South Dakota, Nebraska, Kansas and Oklahoma), and in the Midwest and along lower reaches of the Mississippi river. Switchgrass, though not as competitive as miscanthus in terms of yields and costs of production in most parts of the country, is still produced in a significant amount in northern and central Texas and Wisconsin.

Figure 6.7 presents percentage shares of the land under bioenergy crops (miscanthus and switchgrass) in total available land under the RFS alone and under the RFS and volumetric subsidy scenarios. We find that the percentage share of land under bioenergy crops under the RFS alone achieves the upper limit (25%) mainly in Plain states (Oklahoma and northern Texas), Atlantic states (Kentucky, Tennessee and western South Carolina) , the Southern states (Alabama and Georgia) and Mid-west state Missouri due to higher yields. Biofuel subsidies accompanied with the RFS mandates significantly increase the land allocated to the production of bioenergy crops. Great Plains (South Dakota, Nebraska and Kansas) would increase the land allocated to bioenergy crops. Southern states, such as Louisiana and Mississippi, and Atlantic states (North Carolina, South Carolina and Virginia) would reach the upper limit due to the subsidy.

With the lowland variety of swithchgrass, Figure 6.8 and 6.9 show the spatial distribution of cellulosic feedstocks in 2022 under the biofuel mandates and subsidies. We find that the acreage under switchgrass in 2022 is significantly higher than that with the upland variety, using 3.7 M ha in 2022 under a mandate alone. Under the mandate and subsidy scenario switchgrass would be produced mainly in northern and central Texas, North Dakota, Northern and Central Florida and Pennsylvania where switchgrass is competitive relative to miscanthus. The production of miscanthus is concentrated in the Great Plains (South Dakota, Nebraska, Kansas and Oklahoma), and in the Midwest and along lower reaches of the Mississippi river. In comparison to the mandate and subsidy scenario using the upland variety of switchgrass, the collection of corn stover would slightly decrease in Midwestern states (Illinois, Iowa and Ohio) while the production of wheat straw reduces in Mountain state Montana.

As shown in Figure 6.10, a higher switchgrass yield would increase the land allocated to bioenergy crops in South Dakota and Texas relative to the mandate and subsidy scenario with the upland variety of switchgrass. Southern and western parts of Texas would use the available land for the production of bioenergy crops to the upper limit. Under the mandate and subsidies, only North Dakota allocates additional land to the production of bioenergy crops while percentage shares of the land under bioenergy crops in other regions are not significantly different from that with the upland variety of switchgrass.

6.3 Welfare Effects of Biofuel and Climate Policies in the U.S.

We compare the effects of the various policy scenarios considered above on the cumulative discounted value of social welfare relative to the BAU scenario over the 2007-2022. Social welfare is measured here by the sum of domestic consumers' and producers' surpluses generated in the agricultural and transportation fuel sectors, government expenditures and externality costs (environmental damages) resulting from GHG emissions, over the period 2007-2022. Results with the upland variety of switchgrass are presented in Table 6.4 while Table 6.7 shows welfare results for the lowland variety of switchgrass. Specifically, in comparison with the BAU scenario, a tax of $30 per ton of CO_2e would increase the total social welfare by $118 B (0.7%) by internalizing the GHG externality. This increase in social welfare is attributed to a significant increase in government revenue ($645 B), an increase in agricultural producers' surplus (4%) and a decrease in externality costs resulting from GHG emissions (3%) when the marginal social damages from GHG are valued at $30 per ton of CO_2e. Under the carbon tax, miles consumers' surplus from VMT and consumers' surplus from agricultural commodities are 4% and 1%, respectively, lower than the BAU. However, agricultural producers are better off with an increase in aggregate surplus of 4%.

The biofuel mandates increase the consumers' surplus from VMT and agricultural producers' surplus, and decrease the externality costs of GHG emissions. These welfare gains can compensate for the welfare losses of domestic gasoline producers ($67 B) and agricultural consumers ($62 B), leading to a total social welfare gain of $135 B or 0.8% compared with the BAU scenario. Agricultural producers (both row crop producers and bioenergy crop producers) will be better off and their surplus increases by 19%. Given that the gasoline supply function used in this benchmark scenario is fairly inelastic and the rest of the world accounts for a large share in the reduction of total gasoline consumption, domestic fuel producers will only suffer a loss in surplus of 6%. Miles consumers would be better off by 0.5% due to reduced price of miles relative to the BAU. Externality costs from GHG emissions would decrease by 3% compared with the BAU scenario due to the decreased carbon emission intensity of the blended fuel. As shown in Table 6.7, when the lowland variety of switchgrass is introduced to the production of cellulosic biofuels, it would significantly increase the surplus of biomass producers by $51 B relative to the mandate scenario with the upland variety. That in turn increases agricultural producers' surplus by 23.3% relative to the BAU. Agricultural consumers' surplus would decrease by 2.9% relative to the BAU. Miles consumers' surplus would increase by 0.5% relative to the BAU while the domestic gasoline producers would be worse off with a 5.7% loss in surplus. Total domestic social welfare with the lowland variety of switchgrass would increase by 1.1% relative to the BAU.

When the mandate is combined with subsidies, the gain in total social welfare, relative to the BAU, is lower 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 2% compared to the BAU. Agricultural consumers are now slightly worse off by 0.2% relative to the BAU. The surplus for agricultural producers will increase by 2% compared to the BAU. Agricultural producers' surplus also falls from $171B with the mandate alone to $15 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 $13 B in surplus for the biomass producers relative to the mandate alone. The introduction of the lowland variety of switchgrass would increase agricultural producers' surplus by 5.8%, which is $38 B higher than the upland variety of switchgrass while the effects on miles consumers, agricultural consumers and gasoline producers are similar to that with the upland variety of switchgrass. Total social welfare would be 0.23% higher than the BAU scenario.

In general we find that the overall social welfare under biofuel policies and a carbon tax is higher than the BAU level. However, effects are large for agricultural crop producers and for fuel producers. While the former gains by 2%-23% under all policy scenarios, the latter loses 5%-6% of surplus. Miles consumers gain 2% of surplus under a mandate and subsidies scenario but would lose 4% of surplus under a carbon tax.

6.4 Sensitivity Analysis

We conduct two sets of sensitivity analyses. First we examine the sensitivity of model results on land use, food and fuel prices, GHG emissions and social welfare under the benchmark case with the upland variety of switchgrass to various parameters describing fuel market conditions that are analyzed in the conceptual framework above (see Table 6.8). Specifically, we analyze the impact of (1) doubling the demand elasticity of VMT, from -0.2 to -0.4, (2) increasing the slope of domestic gasoline supply by ten-fold and the supply elasticity of gasoline imports from 2 to 3, and (3) changing the elasticity of substitution between gasoline and ethanol from 3.95 (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 and the processing of cellulosic biofuels, and assumptions about land that can be brought into the production of bioenergy crops (see Table 6.9). Assumptions about cost and technology parameters 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 here considered the low cost of miscanthus and the upland variety of switchgrass production described there. We examine the implications of our assumptions about miscanthus yields, lifetime and costs of production being less optimistic than assumed in the benchmark case. We consider miscanthus lifetime being 10 years instead of 15 years, its yield being 25% lower and its production costs following a high cost scenario (Jain et al. 2009). We investigate the effects of high production costs for miscanthus and low production costs for switchgrass. We examine the implications of reducing growth rates of major crops (corn, soybeans and wheat) by 50%. We also analyze the implications of increasing residue collection rates for corn stover from 30% and 50% under the conventional tillage and no till to 50% and 70%, and for wheat straw from 50% to 70% which may result from potentially high yields of crops and new harvesting machines currently under development. In addition, we examine implications of lowering the upper limit that each region can use total available land to grow bioenergy crops from 25% to 10%, and excluding CRP land from being converted into crop production. We also analyze the effects of increasing the processing cost of cellulosic biofuels in 2022 estimated by EPA (EPA 2009) by 50%, which would increase the conversion cost of cellulosic biofuels over the 2007-2022. In each case, only one parameter is changed at a time while all other parameters remain the same. In Tables 6.8 and 6.9, we report the results for the carbon tax (CT) scenario and the biofuel mandates plus subsidies (MS) scenario.

In Table 6.8 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 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 demand elasticity of miles driven under the CT scenario has a larger negative impact on VMT (-3.6% instead of -2.0%) and leads to a smaller substitution towards corn ethanol (16.1% instead of 21.3%). It also leads to a larger reduction in GHG emissions. On the other hand, the MS scenario leads to a larger increase in VMT and a smaller reduction in GHG emissions than in the benchmark case.

With flatter supply curves for gasoline, the CT reduces gasoline consumption by 3.0% instead of 2.8% and increases ethanol consumption by 25.8% instead of 21.3%. The MS scenario now results in a smaller decline in gasoline price and a larger reduction in gasoline consumption and in GHG emissions (6.3% instead of 5.7%). When the elasticity of substitution between gasoline and ethanol is increased from 3.95 to 10, the CT would lead to a much greater increase in corn ethanol consumption by 46.7% instead of 21.3% 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 consumption and GHG emissions (8.6% instead of 5.7% under the MS in the benchmark case).

In Table 6.9 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 rates at which crop productivity increases is on land used for corn production, on crop prices, on corn ethanol consumption and price, and on the mix of cellulosic feedstocks. Acreage under corn is about 3% higher than in the benchmark case while corn and soybean prices are 12% higher, than in the benchmark case. Acreages under the harvest of corn stover and wheat straw are about 33% less than in the benchmark case. That in turn increases the acreages under miscanthus and switchgrass by 3% and 14%, respectively. Changes in parameters that make miscanthus more expensive by reducing its lifetime, raising its costs of production or reducing its yields have their largest impact on the mix of biofuels produced from corn, corn stover and straw, miscanthus and switchgrass. They reduce acreage under miscanthus in the biofuel mandate and subsidy scenario by 11% to 96%. Acreages under corn stover and wheat straw would be 108%-323% and 219%-1114% higher in these cases than in the benchmark. Acreage under corn would be -0.3% to 33% higher in these cases than in the benchmark while corn prices would be 0.1% to 35% higher. Corn production would need to be increased by 0.1% to 33% to meet the biofuel mandates under the RFS. A higher collection rate of crop residues significantly increases the acreage of corn stover harvest by 212% relative to the benchmark. The acreage under straw, miscanthus and switchgrass decrease by 72%, 28% and 64%, respectively. It also changes the mix of ethanol in favor of cellulosic ethanol that increases by 7% relative to the benchmark. Corn ethanol production decreases by 45% in this case than in the benchmark. Acreage under corn would be 3.4% higher than in the benchmark while corn price would be 3.7% lower.

Lowering the upper limit of the acreage under bioenergy crops from 25% to 10% reduces the land under miscanthus by 26% because it constrains the expansion of miscanthus acreage in most areas. That in turn increases the acreage under switchagrass by 17% in the areas that have lower production costs of switchgrass and did not fully use their land for the production of switchgrass. Acreages under the harvest of corn stover and wheat straw also increase by 183% and 694% relative to the benchmark. It also requires 18% more corn ethanol production than in the benchmark. That leads to increases in corn acreage and price by 3% and 4%, respectively, relative to the benchmark. The exclusion of CRP land significantly decreases the acreages under miscanthus and swithchgrass by 19% and 3%. Acreages under corn stover and wheat straw would be 113% and 353% higher in this case than in the benchmark. The reduction in total land availability reduces the corn acreage by 2%, and as a result increases corn price by 2%.

Higher processing costs of cellulosic ethanol would significantly affect the mix of biofuels such that cumulative consumption of cellulosic ethanol would reduce by 55% relative to the benchmark while cumulative corn ethanol would increase by more than three-fold. Reduced consumption of cellulosic ethanol also leads to a reduction in the acreages under cellulosic feedstocks. Land under miscanthus will decrease by 47% relative to the benchmark, followed by switchgrass and corn stove with 43% and 42% reduction, and the harvest of wheat straw will decline by 35%. Acreage under corn needs to increase by 41% relative to the benchmark to compensate for the reduction in cellulosic feedstocks. That is met by a 4% increase in total land and 9% and 4% reduction in acreages under soybeans and wheat. Corn and soybean prices in 2022 would increase by 46% and 31%, respectively, relative to the benchmark. The costs of corn ethanol and cellulosic ethanol in 2022 would increase 9% and 24%, respectively, relative to the benchmark. That in turn reduces the cumulative consumption of VMT by 0.2% due to increase marginal cost of VMT relative to the benchmark. Across the various parameter changes considered in Table 6.9, we find that none of them has significant impact on VMT, gasoline consumption or GHG emissions.

6.5 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 16% to 47% and increase corn prices by 6% to 12% depending on the parameters describing the fuel sector. The tax would reduce GHG emissions by 3% -4% compared to the BAU scenario. The present value of the welfare gains with the carbon tax is $118 B in the benchmark case and ranges between $88 and $159 B across the various parameter assumptions considered here. The upper end of these ranges would be achieved with a high elasticity of miles demand.

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 due to the high costs of cellulosic biofuels. Miscanthus would meet 91% of the advanced biofuel target, with switchgrass and crop residues meeting the rest. In the benchmark case, the mandate leads to an 20% increase in corn acreage met in part by reducing acreage under soybean and other crops and in part by converting marginal lands to corn. Despite gains in corn productivity over the 2007-2022 period the corn price in 2022 is 26% higher than in the BAU.

The existing volumetric subsidies for cellulosic biofuels make a significant difference to the competitiveness of cellulosic biofuels relative to corn ethanol and shift the mix of biofuels such that 87% of the cumulative biofuels over the 2007-2022 would now be produced from cellulosic feedstocks. This mitigates the competition for land and reduces corn, soybean and wheat prices relative to those with a mandate alone. Corn price in 2022 would now be 10-14% lower than in the BAU while the GHG emissions reduction ranges from 5% to 9% 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 5% to 9% of the BAU levels (over the 2007-2022 period) while the gasoline price in 2022 could be 3% to 9% lower than the BAU level, depending on fuel market parameters (Note: A 7% lower gasoline price in 2022 implies a price of $0.73 per liter which is very close to the gasoline price in 2007).

Our analysis also shows the role of productivity enhancing technologies and conversion of marginal lands to cropland both in the traditional crop sector and the bioenergy sector. Yield increases for major crops like, corn and soybeans and the use of high yielding, long-lived energy crops, like miscanthus contribute to mitigating the competition for land and the impact of biofuel production on food prices. Corn price in 2022 would be 10-13% higher if these technologies are less productive or more costly than assumed in the benchmark case. Land conversion from marginal lands such as idle cropland and cropland pasture, to cropland is likely to reduce the adverse impacts on crop prices. Corn price in 2022 would be 2-4% higher if these marginal lands are not convertible. Because gasoline supply from the rest of the world accounts for a large share of total gasoline consumption in the U.S, domestic gasoline producers would bear a small portion of surplus loss due to the displacement of gasoline by biofuels. We find that the carbon tax and biofuel policies would generate net benefits for the fuel and agricultural sectors relative to the BAU level. Among policies analyzed in the study, we find the biofuel mandate alone generates the largest social welfare while biofuel mandate and subsidy policy achieves the least welfare gain because of a significant government expenditure on biofuel subsidies.

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.

Figures and Tables

Table 6.1: Model Validation for 2007

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

Table 6.2: Effect of Biofuel and Climate Policies on the Agricultural Sector in 2022

	BAU 2007	BAU	Carbon Tax	Mandate	Mandate with Subsidies
			Land Use (M Ha)		
Total land	120.88	123.18	122.26	124.46	118.97
Corn	28.82	29.53	30.45	35.38	24.97
Soybeans	27.98	27.93	27.53	26.13	28.50
Wheat	24.58	26.14	25.39	24.18	25.15
Alfalfa	24.32	23.92	23.87	23.65	23.38
Stover				3.45	5.98
Straw				0.97	1.61
Miscanthus				6.49	12.43
Switchgrass				1.15	1.88
			Crop Production (M MT)		
Corn	270.54	330.31	341.42	394.71	278.36
Soybeans	77.09	84.52	83.73	78.05	89.10
Wheat	59.37	74.15	72.49	68.42	71.98
			Crop Prices ($/MT)		
Corn	111.53	107.35	114.29	135.47	92.99
Soybeans	230.38	243.12	250.32	300.24	224.04
Wheat	203.34	197.11	202.58	214.42	202.59

Table 6.3: Effect of Biofuel and Climate Policies on the Fuel Sector and Emissions

	BAU (2007)	BAU	Carbon Tax	Mandate	Mandate with Subsidies
			Prices in 2022 ($/Km or $/Liter)		
Miles	0.080	0.087	0.097	0.086	0.081
Corn ethanol	0.689	0.656	0.683	0.685	0.522
Cellulosic ethanol				0.766	0.497
Gasoline	0.731	0.785	0.864	0.724	0.730
			Cumulative Consumption over the 2007-2022 Period (B Liters or B Kms)		
Miles		82885.78	81208.59	83110.47	83654.21
Domestic Gasoline		2815.63	2815.63	2787.28	2745.41
Gasoline from ROW		6110.84	6110.84	5892.68	5574.73
Ethanol		326.62	396.33	1220.99	1220.99
Corn		326.62	396.33	801.41	162.19
Stover				16.21	51.14
Straw				1.95	4.10
Miscanthus				381.82	957.53
Switchgrass				19.59	46.03
GHGs (B MT)		29.40	28.56	28.29	27.71

Table 6.4: Effect of Biofuel Policies on Social Welfare ($B or %)[1]

	Carbon Tax	Mandate	Mandate with Subsidies
Miles Consumers	-534.42	70.32	233.31
	-4.03%	*0.53%*	*1.76%*
Domestic Gasoline Producers	-29.25	-67.15	-59.91
	-2.50%	*-5.74%*	*-5.12%*
World Gasoline Producers	-63.70	-142.80	-129.94
	-7.03%	*-15.77%*	*-14.35%*
Agricultural Consumers	-13.93	-61.98	-3.88
	-0.75%	*-3.35%*	*-0.21%*
Agricultural Producers[2]	32.31	171.48	14.56
	3.56%	*18.90%*	*1.61%*
Crop Producers	40.30	202.26	-7.73
	7.82%	*39.23%*	*-1.50%*
Biomass Producers	0.00	2.08	15.42
Livestock Producers	-7.99	-32.86	6.88
	-2.04%	*-8.39%*	*1.76%*
Government Revenue	644.76	0.00	-206.10
Externality Cost	-18.92	-22.82	-34.70
	-2.85%	*-3.44%*	*-5.23%*
Total Welfare[3]	118.39	135.49	12.69
	0.72%	*0.82%*	*0.08%*[3]

1. Percentage change in italics is relative to the BAU level.
2. Agricultural producers' surplus includes surplus from crop producers, biomass producers and livestock producers.
3. Total social welfare only includes calculation does not include world gasoline producers.

Table 6.5: Sensitivity of Land Use, Crop Production and Prices to Switchgrass Yield

	Mandate	Mandate with Subsidies
Land Use in 2022 (M Ha)		
Total land	125.95	120.51
Corn	35.51	25.65
Soybeans	26.37	28.65
Wheat	24.90	25.89
Alfalfa	23.82	23.71
Stover	3.31	7.87
Straw	0.59	1.75
Miscanthus	5.17	10.40
Switchgrass	3.67	4.13
Crop Production in 2022 (M MT)		
Corn	395.47	286.91
Soybeans	78.94	88.03
Wheat	70.69	74.03
Crop Prices in 2022 ($/MT)		
Corn	131.98	96.80
Soybeans	293.73	223.37
Wheat	208.66	196.22

Table 6.6: Sensitivity of Miles, Fuel Mix and Emissions to Switchgrass Yield

	Mandate	Mandate with Subsidies
Prices in 2022 ($/Km or $/Liter)		
Miles	0.088	0.081
Corn ethanol	0.678	0.524
Cellulosic ethanol	0.924	0.520
Gasoline	0.721	0.729
Cumulative Consumption over the 2007-2022 Period (B Liters or B Kms)		
Miles	83090.62	83599.24
Domestic Gasoline	2787.28	2745.16
Gasoline from ROW	5892.68	5572.85
Ethanol	1220.99	1220.99
Corn	802.51	249.98
Stover	29.69	79.49
Straw	1.71	12.23
Miscanthus	300.31	668.76
Switchgrass	86.77	210.53
GHGs (B MT)	28.30	27.82

Table 6.7: Sensitivity of Social Welfare Over 2007-2022 to Switchgrass Yield ($B or %)[1]

	Mandate	Mandate with Subsidies
Miles Consumers	65.53	216.79
	0.49%	*1.63%*
Domestic Gasoline Producers	-67.32	-60.78
	-5.76%	*-5.20%*
World Gasoline Producers	-143.15	-131.21
	-15.81%	*-14.49%*
Agricultural Consumers	-54.30	-7.17
	-2.94%	*-0.39%*
Agricultural Producers[2]	211.47	52.66
	23.31%	*5.80%*
Crop Producers	189.65	11.82
	36.78%	*2.29%*
Biomass Producers	53.01	37.58
Livestock Producers	-31.19	3.26
	-7.97%	*0.83%*
Government Revenue	0.00	-195.76
Externality Cost	22.56	32.20
	-3.40%	*-4.85%*
Total Welfare[3]	177.94	37.93
	1.08%	*0.23%*

1. Percentage change in italics is relative to the BAU level.
2. Agricultural producers' surplus includes surplus from crop producers, biomass producers and livestock producers.
3. Total social welfare calculation does not include world gasoline producers.

Table 6.8: Sensitivity to Fuel Sector Parameters[1]

	Benchmark[2]		$\varepsilon_m^d = -0.4$		Larger ε_g^s		$\sigma = 10$	
	CT[3]	MS	CT	MS	CT	MS	CT	MS
Changes in Land Uses (%)								
Total Land	-0.74	-3.42	-0.74	-3.35	-0.14	-2.91	0.13	-3.38
Corn	3.10	-15.43	2.70	-14.88	3.26	-13.39	7.29	-16.28
Soybeans	-1.44	2.03	-0.96	2.10	-1.19	1.48	-2.12	1.58
Wheat	-2.87	-3.79	-3.29	-4.07	-3.18	-4.00	-3.13	-4.77
Cellulosic Feedstock Acres (M Ha)								
Stover		5.98		5.86		5.87		8.10
Straw		1.61		1.61		1.61		1.78
Miscanthus		12.43		12.37		12.37		13.70
Switchgrass		1.88		1.88		1.76		2.17
Changes in Crop Production and Prices (%)								
Corn Production	3.36	-15.73	2.90	-14.56	3.60	-13.03	7.23	-16.99
Corn Price	6.46	-13.38	6.88	-13.38	10.16	-10.36	12.29	-13.84
Soybeans Production	-0.94	5.41	-0.49	5.76	-0.84	5.89	-1.50	3.56
Soybeans Price	2.96	-7.85	3.38	-7.28	4.69	-5.47	5.01	-3.15
Wheat Production	-2.23	-2.93	-2.14	-3.00	-2.35	-3.20	-3.20	-4.17
Wheat Price	2.77	2.78	3.25	3.60	2.31	3.17	4.50	4.18
Changes in Fuel Prices and Consumption and Mile Consumption (%)								
Gasoline Price	10.06	-7.01	9.38	-6.30	11.57	-3.46	10.06	-9.30
Corn Ethanol price	4.12	-20.43	4.41	-20.82	5.38	-19.66	5.28	-21.42
Cellulosic Ethanol Price ($/Liter)		0.50		0.50		0.50		0.50
Gasoline Consumption	-2.76	-6.13	-4.26	-5.41	-3.01	-6.79	-3.21	-9.23
Corn Ethanol Consumption	21.34	-50.34	16.07	-48.97	25.74	-46.06	46.74	-40.24
Cellulosic Ethanol (B Liters)	0.00	1058.80	0.00	1058.84	0.00	1058.75	0.00	1337.15
Mile Consumption	-2.02	0.93	-3.64	1.76	-2.19	0.48	-1.95	1.37
Changes in Social Welfare and GHG Emissions (%)								
GHGs	-2.84	-5.73	-4.33	-4.81	-3.08	-6.30	-3.14	-8.58
Social Welfare	0.72	0.08	1.62	0.02	0.56	-0.38	0.90	0.56

1. % change is calculated relative to baseline (BAU) results where baselines change with different parameters;
2. Benchmark scenario is defined as the one with the upland variety of switchgrass.
3. CT denotes carbon tax policy, and MS represents the policy of consumption mandates plus subsidies.

Table 6.9: Sensitivity to Technology and Cost Parameters[1]

	Rate of yield increase reduced by 50%	Upper limit on energy crop acres reduced from 25% to10%	Higher rates of residue collection	Exclusion of CRP land	Higher Processing Cost of Cellulosic Ethanol
Changes in Land Uses (%)					
Total Land	0.87	0.17	1.89	-1.01	4.43
Corn	2.92	3.16	3.42	-2.32	41.08
Soybeans	0.62	-1.80	3.37	-2.28	-8.75
Wheat	0.08	0.96	3.70	-4.60	-3.92
Cellulosic Feedstock Acres					
Stover	-31.69	183.53	211.98	113.44	-41.42
Straw	-33.31	694.02	-72.10	353.43	-35.37
Miscanthus	2.62	-26.35	-28.02	-18.91	-46.79
Switchgrass	13.82	16.91	-64.11	-3.30	-42.74
Changes in Crop Production and Prices (%)					
Corn Production	-4.48	4.13	3.50	-0.88	41.87
Corn Price	11.97	3.86	-3.66	1.92	45.66
Soybeans Production	-6.04	-3.55	1.17	-3.00	-12.06
Soybeans Price	11.59	2.75	3.02	2.84	31.37
Wheat Production	-7.34	-0.30	3.27	-2.90	-4.83
Wheat Price	7.56	-0.64	-3.27	1.68	6.29
Changes in Fuel Prices and Consumption and Mile Consumption (%)					
Gasoline Price	0.00	-0.14	0.00	-0.08	-0.41
Corn Ethanol price	3.83	1.15	-0.19	-0.81	8.81
Cellulosic Ethanol Price	-0.40	6.84	-0.40	4.13	24.35
Gasoline Consumption	-0.01	-0.07	-0.03	-0.08	-0.26
Corn Ethanol	-1.31	17.56	-44.89	60.49	357.40
Cellulosic Ethanol	0.20	-2.69	6.88	-9.27	-54.75
Mile Consumption	-0.01	-0.07	-0.03	-0.08	-0.24
Changes in Social Welfare and GHG Emissions (%)					
GHGs	-0.14	0.14	-0.15	0.28	1.82
Social Welfare	0.01	0.00	-0.09	0.14	0.42

1. Percentage changes are calculated relative to the same policy scenario in the benchmark case with the upland variety of switchgrass.

Table 6.9 Continued:

	Lifetime of miscanthus reduced from 15 to 10 years	High cost of production of energy crops	25% decrease in miscanthus yield	High cost of production of miscanthus
Changes in Land Uses (%)				
Total Land	0.10	3.40	-0.32	1.36
Corn	-0.29	32.71	1.20	25.14
Soybeans	0.72	-6.72	-1.80	-7.03
Wheat	0.45	-1.24	-1.22	-3.32
Cellulosic Feedstock Acres				
Stover	107.93	267.10	162.63	323.46
Straw	219.24	1114.20	549.44	910.21
Miscanthus	-11.10	-61.75	-10.82	-96.25
Switchgrass	68.85	-63.32	213.61	717.07
Changes in Crop Production and Prices (%)				
Corn Production	0.06	33.17	2.39	28.23
Corn Price	0.06	34.54	3.90	31.45
Soybeans Production	-0.30	-10.03	-3.14	-9.43
Soybeans Price	-0.23	25.68	2.66	23.43
Wheat Production	-0.01	-3.10	-1.03	-3.19
Wheat Price	0.18	5.13	0.32	4.35
Changes in Fuel Prices and Consumption and Mile Consumption (%)				
Gasoline Price	0.00	-0.27	-0.14	-0.27
Corn Ethanol price	-0.57	7.28	1.34	8.43
Cellulosic Ethanol Price	2.21	12.88	6.04	13.28
Gasoline Consumption	-0.06	-0.18	-0.07	-0.13
Corn Ethanol	20.19	244.99	10.72	126.07
Cellulosic Ethanol	-3.09	-37.53	-1.64	-19.31
Mile Consumption	-0.06	-0.16	-0.07	-0.12
Changes in Social Welfare and GHG Emissions (%)				
GHGs	0.17	1.34	0.35	1.18
Social Welfare	-0.03	0.24	-0.06	0.07

1. Percentage changes are calculated relative to the same policy scenario in the benchmark case with the upland variety of switchgrass.

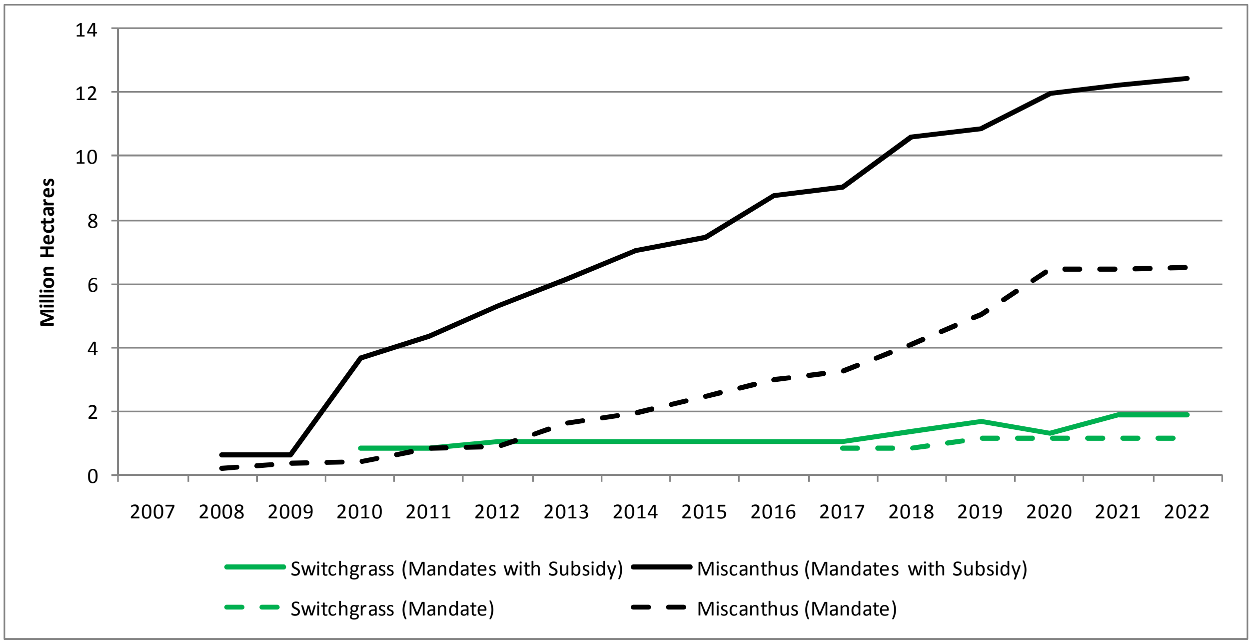


Figure 6.1: Land Under Bioenergy Crops with Upland Variety of Switchgrass

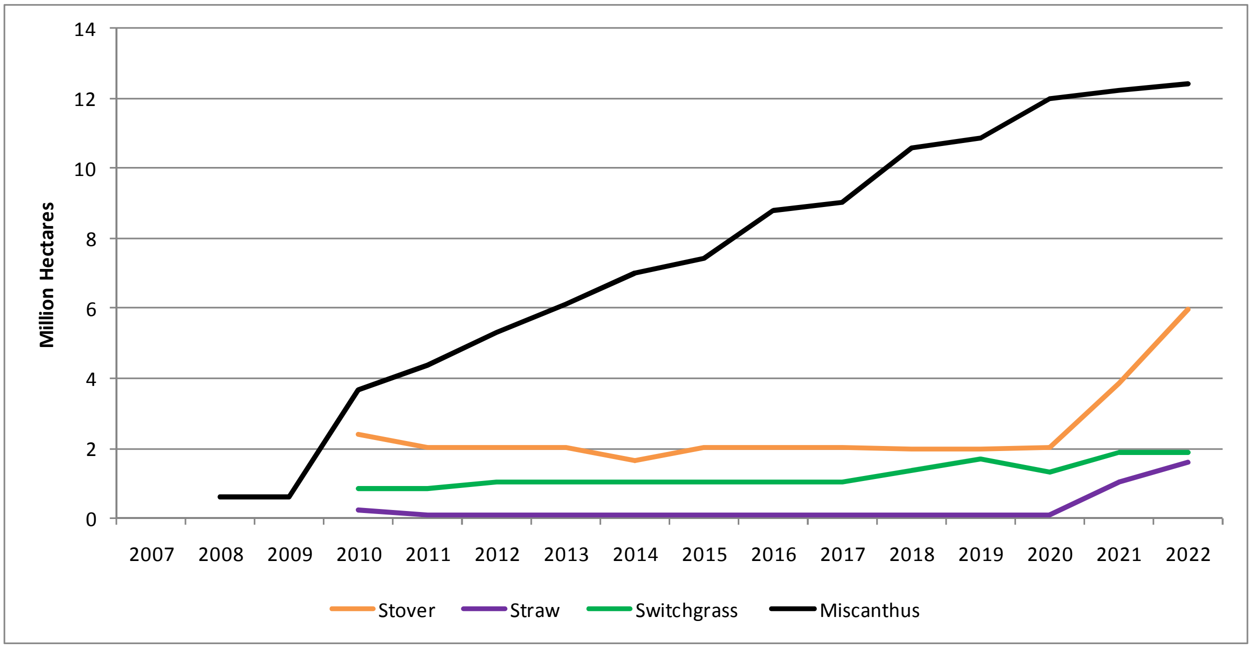


Figure 6.2: Land Under Cellulosic Feedstocks Under Mandates and Subsidies with Upland Variety of Switchgrass

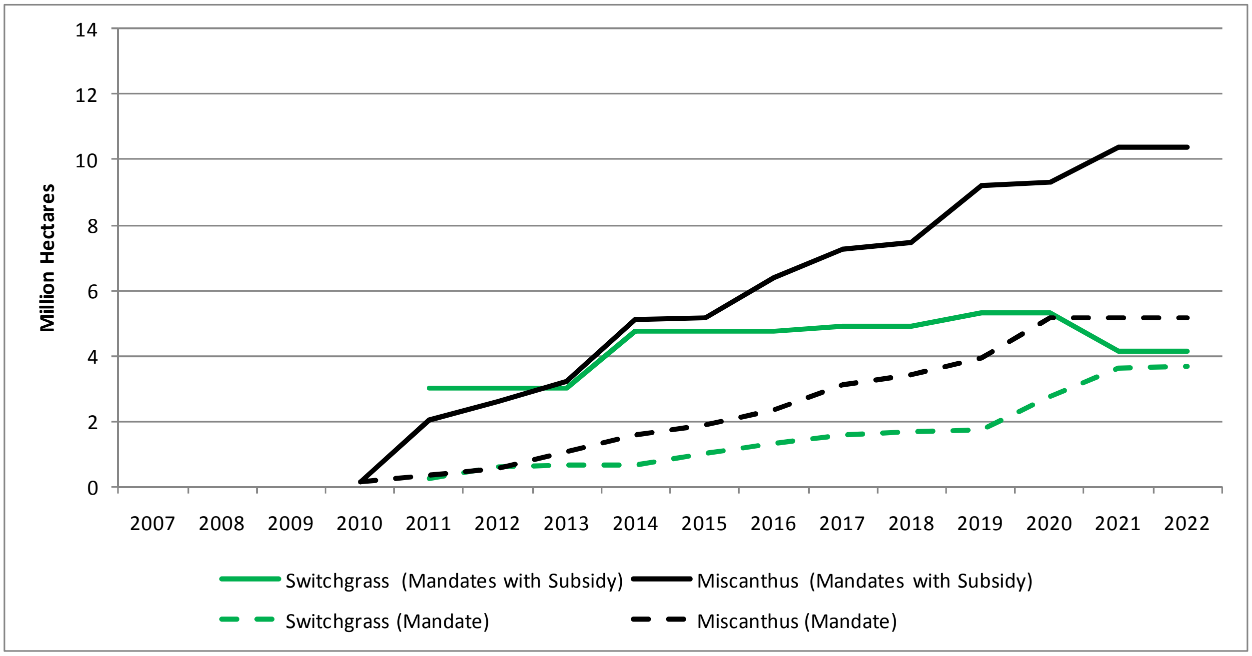


Figure 6.3: Land Under Energy Crops with Lowland Variety of Switchgrass

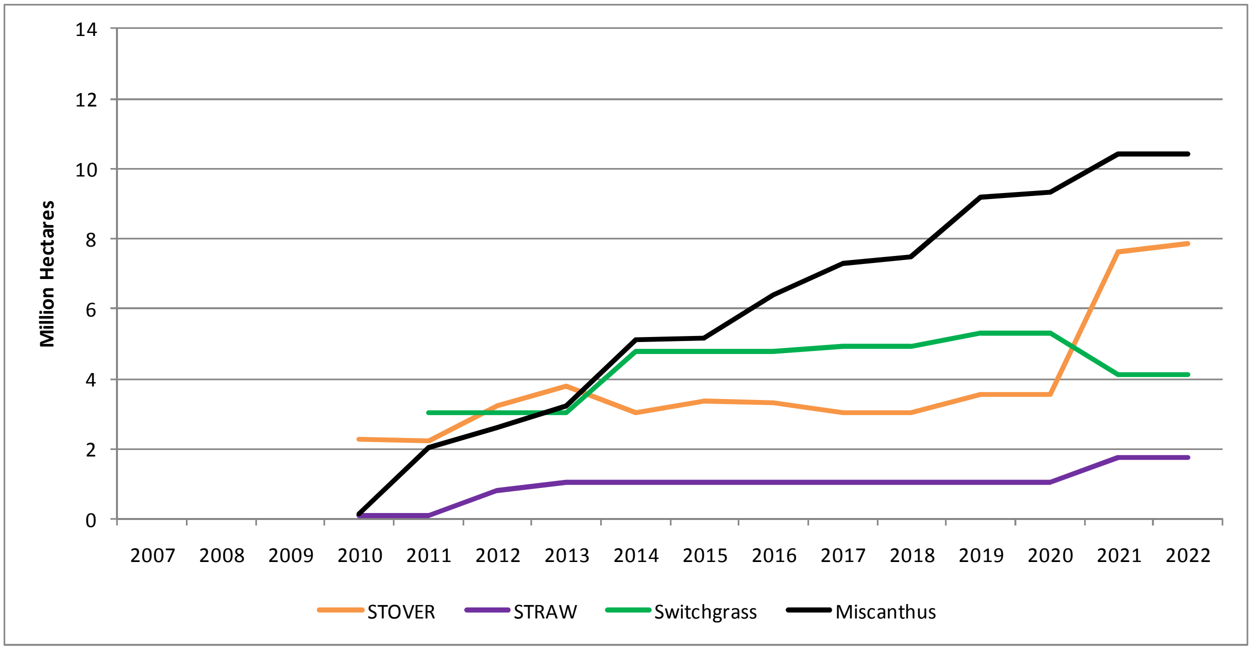


Figure 6.4: Land Under Cellulosic Feedstocks Under Mandates and Subsidies with Lowland Variety of Switchgrass

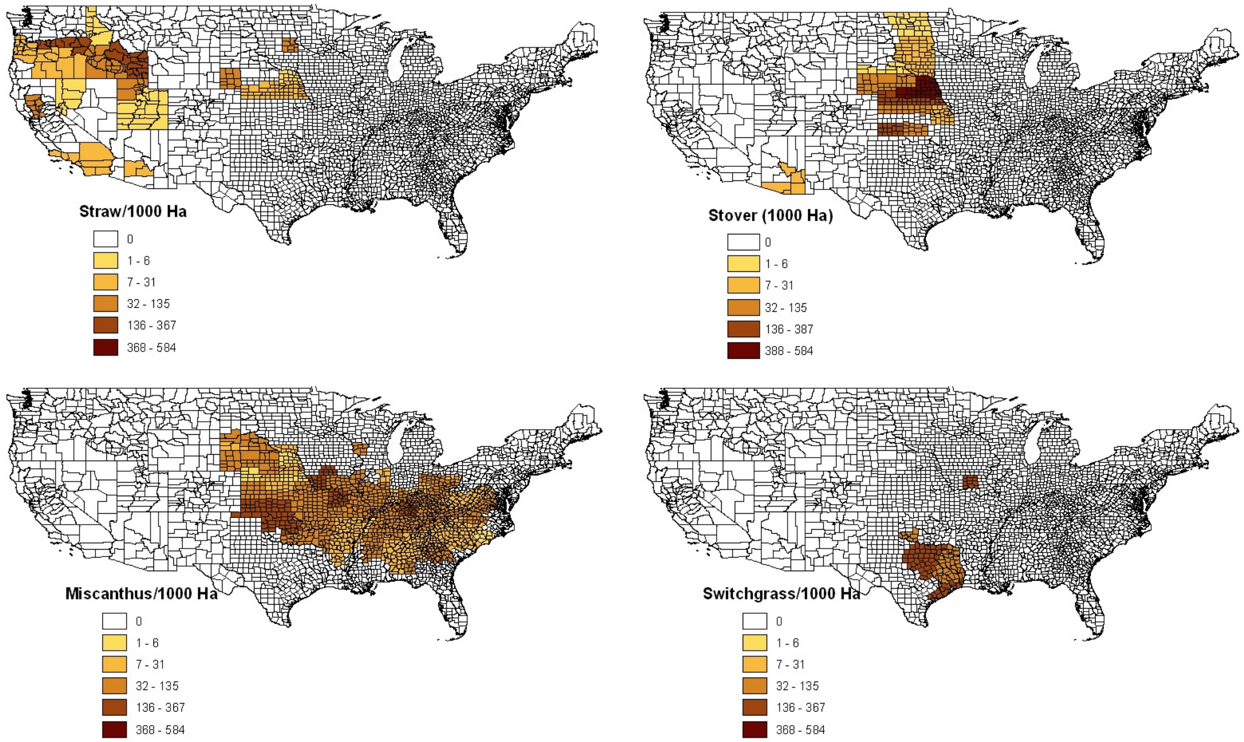


Figure 6.5: Spatial Distribution of Cellulosic Feedstocks Under Mandates with Upland Variety of Switchgrass

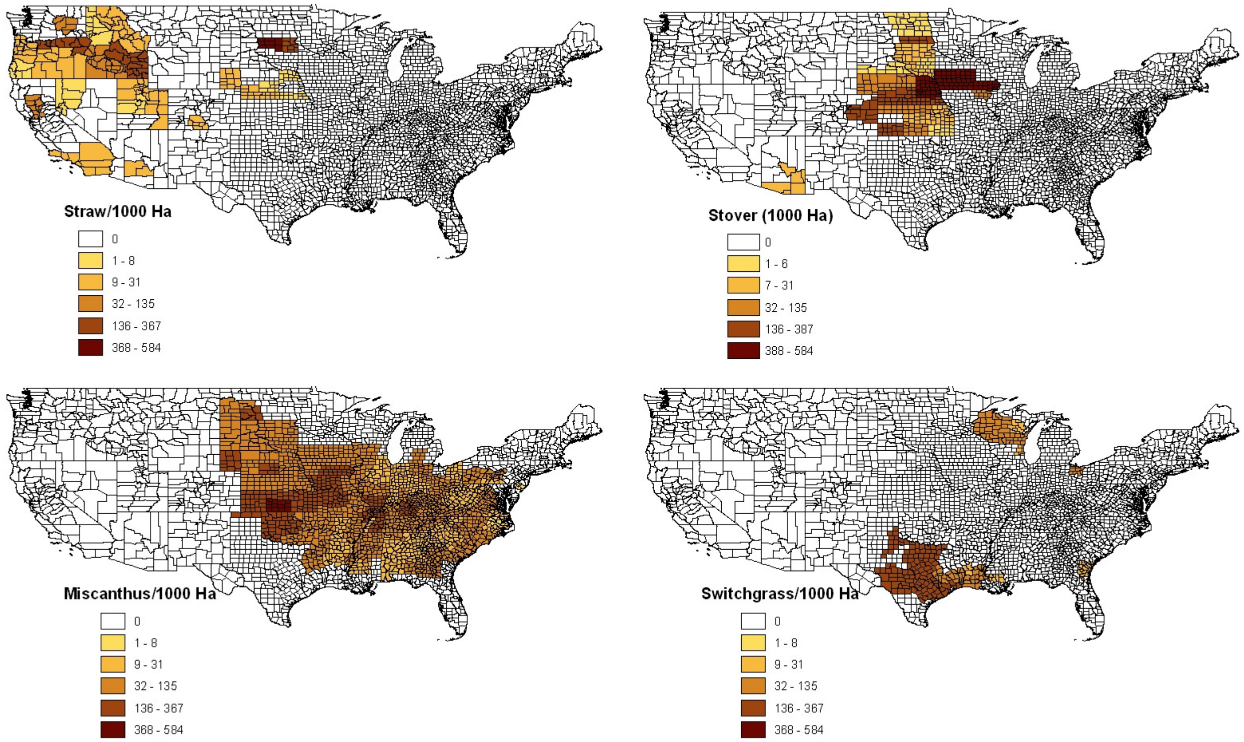


Figure 6.6: Spatial Distribution of Cellulosic Feedstocks Under Mandates and Subsidies with Upland Variety of Switchgrass

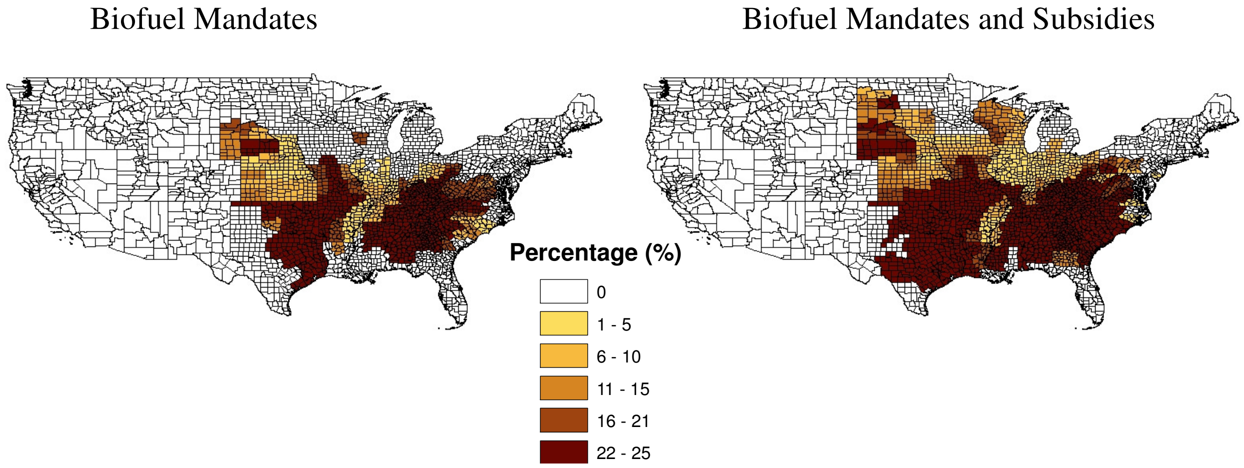
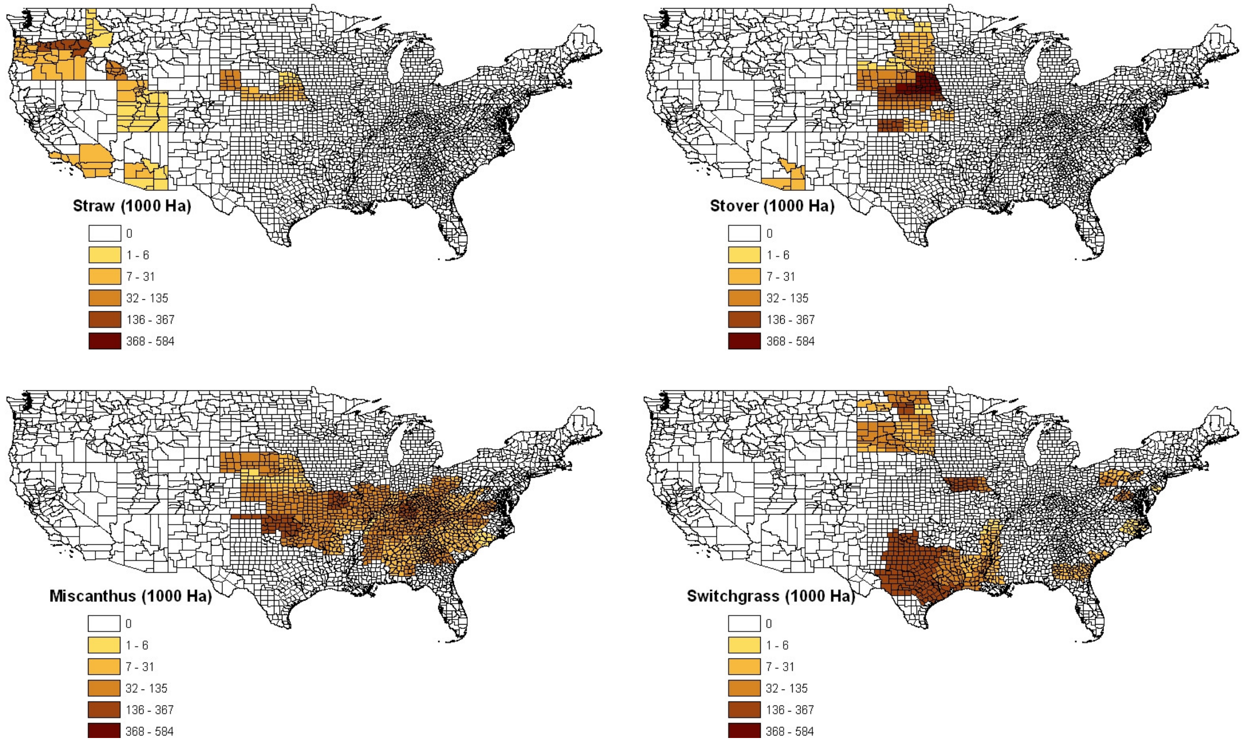


Figure 6.7: Share of Land Under Bioenergy Crops in Total Land with Upland Variety of Switchgrass

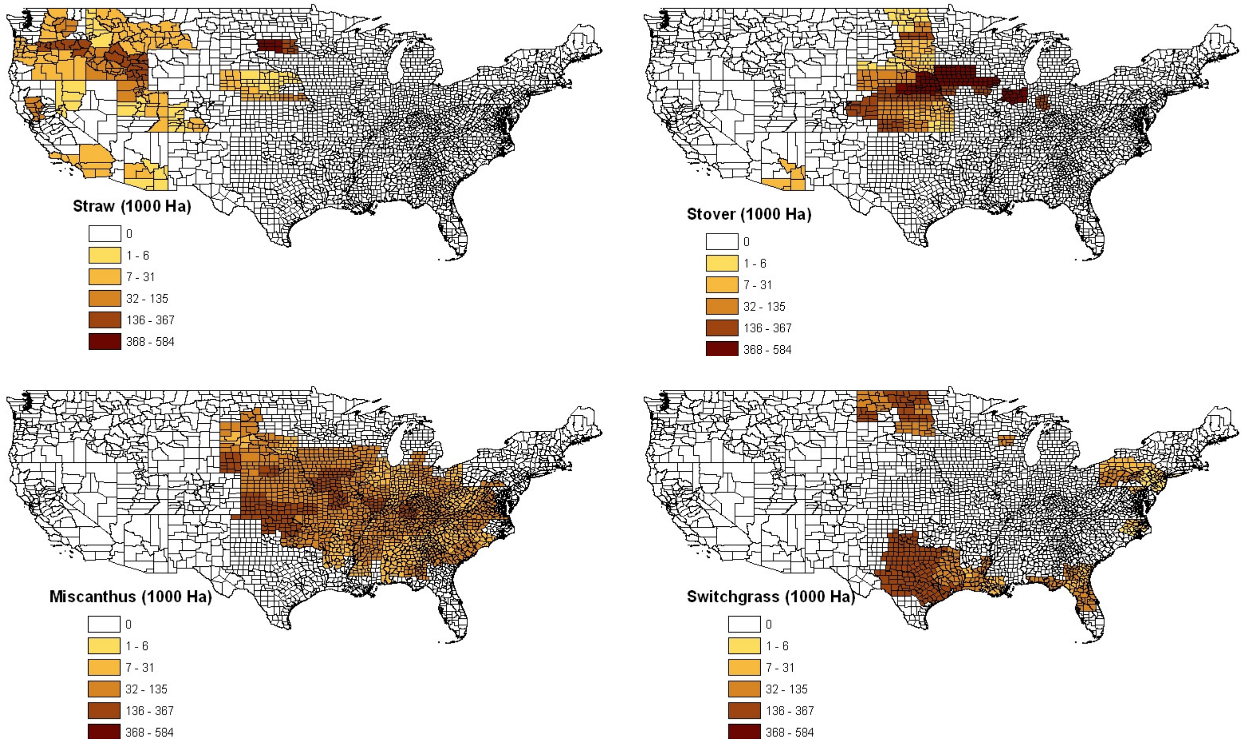

Straw (1000 Ha)

Stover (1000 Ha)

Miscanthus (1000 Ha)

Switchgrass (1000 Ha)

Figure 6.8: Spatial Distribution of Cellulosic Feedstocks Under Mandates with Lowland Variety of Switchgrass

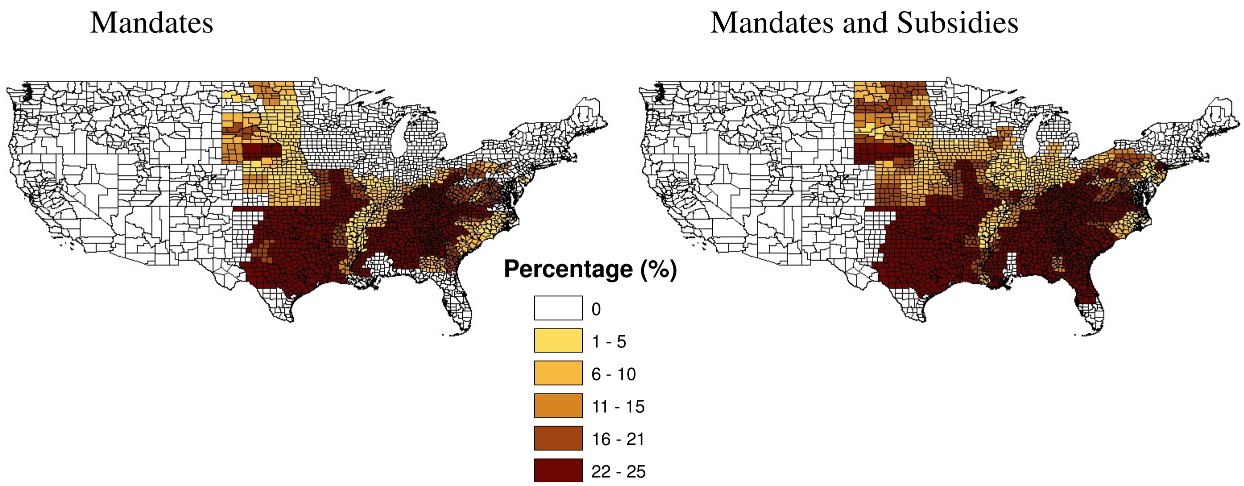

Straw (1000 Ha)

Stover (1000 Ha)

Miscanthus (1000 Ha)

Switchgrass (1000 Ha)

Figure 6.9: Spatial Distribution of Cellulosic Feedstocks Under Mandates and Subsidies with Lowland Variety of Switchgrass


Mandates

Mandates and Subsidies

Figure 6.10: Share of Acreages Under Bioenergy Crops with Lowland Variety of Switchgrass

Chapter 7: Liberalization of Trade in Biofuels: Implications for GHG Emissions and Social Welfare

The recently enacted Energy Independence and Security Act (EISA) of 2007 places a greater emphasis on the next generation of biofuels and establishes the Renewable Fuel Standard (RFS) that mandates that 80 of the 136 B liters of ethanol in 2022 should be advanced biofuels that reduce GHG emissions by at least 50% relative to conventional gasoline. Of the 80 B liters of advanced biofuels in 2022, the RFS requires that at least 60 B should be cellulosic biofuels derived from ‘renewable biomass’ and achieving a lifecycle GHG emission displacement of 60% compared to conventional gasoline. Sugarcane ethanol from Brazil can reduce GHG emissions by 70% relative to gasoline, and qualifies as an advanced biofuel; thus the maximum amount of sugarcane ethanol imports under the category of advanced biofuels can be up to 20 B liters in 2022. In addition, sugarcane ethanol can compete with corn ethanol to meet 56 B liters of conventional biofuels in 2022. However, to protect domestic biofuel industry import tariffs are imposed by the U.S. to restrict ethanol imports from Brazil. Sugarcane ethanol from Brazil is cheaper than cellulosic ethanol and under certain market conditions even cheaper than corn ethanol (Lasco et al. 2009). Depending on the competitiveness of sugarcane ethanol relative to domestic biofuels, these tariffs distort not only the mix of biofuels consumed but affect the GHG mitigation benefits of displacing gasoline using biofuels.

While trade liberalization is expected to increase the imports of sugarcane ethanol, the effect on overall GHG emissions is ambiguous. It depends on the types of biofuels that are replaced by sugarcane ethanol since sugarcane ethanol is more GHG intensive than cellulosic biofuels which can reduce GHG emissions by over 90% relative to gasoline. That in turn depends on the level of import tariffs and the competitiveness of sugarcane ethanol relative to corn ethanol and cellulosic ethanol. Moreover, since the U.S. is a large buyer of sugarcane ethanol, it is expected to influence the world price of ethanol. Thus, the extent to which sugarcane ethanol can be imported depends on the response of imported ethanol to the world price of ethanol. If the elasticity of supply of imported ethanol is large (or the world price of ethanol is given), the removal of a tariff would lead to a reduction in the price of domestic biofuels at the same level as the tariff and a large increase in ethanol import. However, if the elasticity of supply is small (or the US can influence the world price of ethanol), the effect of trade liberalization would be smaller.

In this chapter we first expand BEPAM developed in chapter 4 to include trade in biofuels and analyze the welfare effect of the trade liberalization in biofuels and its implication for GHG emissions. Second, we explore the economically viable mix of biofuels from alternative feedstocks in an open economy under different policy scenarios and analyze the implications for cropland allocation and for food and fuel prices.

7.1 Scenarios and Results

Using existing fuel taxes, tax credits and import tariffs for corn ethanol and sugarcane ethanol, we first compare the model results on land allocation, fuel consumption, biofuel imports and commodity prices with the observed values in 2007 to validate our simulation model. As shown in Table 7.1, the differences in land allocation between model results and observed are generally less than 10% except for acreages under corn and sorghum that are -10.2% and 10.3% deviations from the observed values. Deviations for commodity prices are typically less than 15%. The fuel prices, fuel consumption and biofuel imports are within 10% deviations from the observed values with an exception of ethanol imports that is 12% lower than the observed value in 2007.

We construct a business as usual (BAU) scenario that is defined as one without biofuel policy. We then compare the effects of three policy scenarios to the BAU on the agricultural and fuel sectors, including biofuel mandates under the RFS alone (M), biofuel mandates with volumetric tax credits (MS) and biofuel mandates with volumetric tax credits and import tariffs (MST). In all scenarios considered in the model simulations, we include data on growth for demand for agricultural commodities and VMT, crop productivity and technological progress in biofuel refineries. The RFS mandates are set as the volumetric requirements for the production of biofuels at mandated levels for the period of 2007-2022. These mandates serve as the minimum quantity restriction of biofuel production that can shift up if economically competitive with conventional fuels through policy support and technological improvements. Table 7.2 summarizes the results on land use, crop production and crop prices while Table 7.3 displays the effects on the fuel sector.

7.1.1 Effects of Biofuel Policies on the Agricultural and Fuel Sectors

Business-As-Usual (BAU): In the absence of any government intervention in the biofuels market we find that total crop acreage increases by less than 2% from 120.8 M to 122.9 M ha with corresponding reductions in pasture land. Corn and wheat acreage would increase by 0.5 M ha (2%) and 1.5 M ha (6%) over the 2007-2022 period while acreage under soybean slightly decreases. Corn production will increase by 21% to meet the increasing demand for corn ethanol. However corn price in 2022 decreases by 0.3% in 2022 due to a 21% increase in corn yield per hectare. In the fuel sector, we find a 9% increase in the price of VMT and 7% increase in gasoline price in 2022 compared to 2007. Corn ethanol production would be about 24 B liters in 2022 while ethanol imports would be 3 B liters in 2022, which are 77% and 48% higher than their levels in 2007.

Biofuel Mandate (M): A binding biofuel mandate would require the production of about 790 B liters of corn ethanol, 377 B liters of cellulosic ethanol and 55 B liters of sugarcane ethanol imports over the 2007-2022 period. Cumulative production of corn ethanol and ethanol imports would increase by 175% and 25%, respectively, relative to the BAU over the 2007-2022 period. Of the 377 B liters of cellulosic ethanol, about 84% and 4% are made from miscanthus and switchgrass while biofuels from corn stover and wheat straw account for 12% and 1%, respectively. Of the 55 B liters of ethanol imports, about 78% (43 B) would be used to meet the mandate of advanced biofuels (420 B liters) over the 2007-2022 period.

The biofuel mandate results in a reduction in gasoline consumption over the period of 2007-2022 by 7% and a reduction in gasoline price in 2022 by 8% compared to the BAU levels. The reduction in gasoline supply from the rest of the world accounts for 88% of the total gasoline consumption reduction over the period of 2007-2022. The costs of cellulosic biofuels and sugarcane ethanol are $0.81 per liter of biofuel, higher than the cost of corn ethanol ($0.68 per liter) and gasoline ($0.72 per liter) in 2022. However, the displacement of gasoline lowers the overall cost of VMT and as a result the VMT increases by 0.3% relative to the BAU scenario in 2022. The volumetric share of ethanol in total fuel consumption increases to 13% over the 2007-2022 period while advanced biofuels account for 35% of total biofuel consumption. Reduced GHG intensity of the blended fuel reduces cumulative GHG emissions by 1.1 B metric tons (or 4%) relative to BAU.

The mandate leads to three types of impacts on cropland uses. First, it increases total cropland by 1.6% (2.0 M ha) in 2022 through the conversion of marginal lands. Second, it results in a 22% (6.4 M ha) increase in land under corn in 2022 compared to the BAU. Land under pasture, soybeans, wheat, sorghum, barley, rice and cotton would reduce by about 4.5 M ha.

Third, about 6.2 M ha needs to be converted to miscanthus production and 0.8 M ha for switchgrass production; of 7 M ha under bioenergy crops, only 0.5 M ha is converted from cropland and 6.5 M ha from marginal lands. Corn stover and wheat straw would be harvested from 10% and 3% of the land under corn and wheat, respectively. Corn and soybean prices in 2022 are 24% and 21% higher than under the BAU.

Biofuel Mandate and Volumetric Subsidies (MS): The provision of tax credits for biofuels reduce the consumer price of biofuels to $0.51 per liter which is significantly lower than that under a mandate alone. In response to lower price of biofuels, sugarcane ethanol imports would decrease by 2.4% over the 2007-2022 period relative to the BAU. Due to the volumetric subsidies, cellulosic ethanol would become competitive with corn ethanol and as a result cumulative corn ethanol production reduces from 790 B liters under the RFS to 259 B liters. Cumulative cellulosic ethanol production is more than twice of that under a mandate alone from 377 B liters to 920 B liters over the 2007-2022 period. That is met by an increase in 488 B liters of ethanol from miscanthus and increases in ethanol from switchgrass and crop residues being 55 B liters. The share of cumulative cellulosic ethanol in total biofuel consumption over the 2007-2022 period further increases from 35% under a mandate alone to 97%.

In addition, the subsidies reduce the consumer price of VMT from $0.087 per Km under a mandate to $0.081 per Km. That in turn increases cumulative VMT over the 2007-2022 period by 500 B kilometers (0.6%) relative to a mandate alone. Gasoline price and consumption are marginally higher than that under the mandate alone due to increased consumption of the blended fuel. The mandate and subsidies scenario results in the displacement of 550 B liters of gasoline (6%) relative to the BAU scenario while increasing the cumulative biofuel production by 890 B liters over the 2007-2022 period. The biofuel subsidies result in further decline in GHG emissions relative to the mandate alone and the BAU because they induce a switch away from gasoline and corn ethanol towards cellulosic ethanol. The total GHG emissions would now be decreased by about 5% relative to the BAU scenario over the 2007- 2022 period.

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 in 2022 diminishes by about 5.3 M ha relative to the mandate alone since a larger portion of the mandate is met by high yielding feedstock, such as miscanthus, instead of corn. The increase in biofuels produced from miscanthus leads to an increase in the land under miscanthus from 6.2 M ha under a mandate alone to 11.9 M ha under a mandate and subsidies. It also increases the acreage from which corn stover and wheat straw are harvested. In comparison to the BAU, the demand for total cropland in 2022 decreases by 3.3 M ha while land under corn decreases by 3.8 M ha. Corn price and corn production in 2022 decline by about 13% and 12%, respectively, relative to the BAU.

Biofuel Mandate with Volumetric Subsidies and Import Tariffs (MST): With the imposition of import tariffs, sugarcane ethanol would have to go through CBI countries to avoid the tariffs. That result in a reduction in ethanol imports from Brazil by 12 B liters relative to the MS scenario while CBI countries only increase ethanol supply to the U.S. by 0.1 B liters due to the limitation on production capacity. Corn ethanol and cellulosic ethanol would increase by 5 B and 7 B liters, respectively, to compensate the reduction in ethanol imports relative to the MS scenario. Biofuel prices are also marginally higher than those under the MS scenario, which induces a switch away from swithchgrass towards high-yielding miscanthus and crop residues. In comparison to the BAU scenario, ethanol imports would decrease by 30% over the 2007-2022 period. Since the volumetric share of ethanol imports only accounts for 2.5%, the effects on the mix of biofuels from corn and other cellulosic feedstocks are small relative to the MS scenario.

Imposing import tariffs would have negative effects on cumulative gasoline consumption and VMT over the period of 2007-2022 relative to the MS. It also increases food prices by diverting cropland from the production of food crops to the production of fuel crops, and raises GHG emissions. However these effects are not significant relative to the MS scenario (less than 1%).

7.1.2 Welfare Effects of Biofuel Policies

We compare social welfare changes for each scenario considered here relative to the BAU scenario. Social welfare is measured by the sum of cumulative discounted value of consumers' and producers' surplus in the agricultural and transportation fuel sectors, government expenditures and externality damages resulting from GHG emissions over the period 2007-2022 in the US. Results are shown in Table 7.4.

The biofuel mandates would increase the total social welfare by 0.9% compared to the BAU. This increase in social welfare can be attributed to increases in miles consumers' surplus by 0.5% due to lower miles prices, agricultural producers' surplus by 21.4% and a decrease in externality costs by 3.3% resulting from GHG emissions when the marginal social damages from GHG are valued at \$30 per ton of CO2e. Under the mandates, domestic gasoline producers' surplus and agricultural consumers' surplus are 5.8% and 3.3%, respectively, lower than the BAU.

The provision of subsidies accompanied with biofuel mandates would reduce the net gain in domestic social welfare relative to the BAU compared to a mandate alone. That is because it results in a large government expenditure (\$190 B). Miles consumers will gain in surplus of about 1.6% relative to the BAU. Domestic gasoline producers will have a surplus loss of 5.2% compared to the BAU. Agricultural consumers are worse off by 0.9% relative to the BAU while the surplus for agricultural producers will be \$135 B lower than a mandate alone, but still 7.4%

higher than the BAU. The reduction in the surplus of agricultural producers is in large due to reduced crop prices and production, resulting in lower surplus for row crop producers. Externality costs from GHG emissions would decrease by 4.8% relative to the BAU.

The imposition of import tariffs together with the biofuel mandates and subsidies creates a 0.3% higher social welfare relative to the BAU that is because it leads to a larger increase in miles consumers' surplus (1.6%), agricultural producers' surplus (7.6%) , and a reduction in externality cost (4.8%). Domestic gasoline producer would be worse off with a surplus loss by 5.2%. Agricultural consumers' surplus would reduce by 1% relative to the BAU scenario. Government expenditure on ethanol subsidies would be $189 B relative to the BAU.

We find the domestic social welfare under biofuel policies is higher than the BAU level because foreign gasoline producers would bear a large portion of the cost (14.4%-15.7% relative to the BAU) of meeting the biofuel mandates. Miles consumers gain about 0.5%-1.6% under alternative policy scenarios relative to BAU while domestic gasoline producers lose about 5.2%-5.8%. Agricultural producers gain 7.4%-21.4% of surplus under biofuel policies relative to BAU while agricultural consumers lose 1%-3.3% of surplus. Externality costs due to GHG emissions will decrease by 0.3%-0.9% relative to the BAU.

7.2 Sensitivity Analysis

We conduct sensitivity analysis for parameters that can influence sugarcane ethanol imports. We first double elasticities of ethanol supply from Brazil and CBI countries, from 2.7 to 5.4. We then double the growth rate of sugarcane ethanol production in Brazil, from 8% to 16%, which would reduce the production cost of sugarcane ethanol through learning by doing. We examine the robustness of model results on land use, crop production and crop prices, fuel consumption and fuel prices, GHG emissions and social welfare. In each case, only one parameter changes at a time while others remain the same. Table 7.5 presents the results for the scenarios of the M and MST. We report the results as percentage deviations compared to the corresponding BAU with the same parameters.

We find that doubling the elasticity of ethanol imports increases cumulative ethanol imports by 49% instead of 25% under the mandate scenario. That leads to a reduction in the consumption of cellulosic ethanol (351 B liters instead of 377 B liters). Corn ethanol consumption in the BAU and mandate scenarios is also smaller than that under the benchmark case (277 B and 785 B liters instead of 288 B and 790 B liters). That results in a higher percentage increase in corn ethanol consumption under the mandate scenario relative to the benchmark (184% instead of 75%). The MST scenario now results in a grater decrease in ethanol imports (46% instead of 29%) and increases in corn ethanol and cellulosic ethanol. The effects of increasing the elasticity of ethanol imports on food production and prices, and gasoline consumption and price in both scenarios are not significantly; that suggests that our model results are robust to this assumption.

With the growth rate of sugarcane ethanol in Brazil doubling, ethanol imports are about 3 B liters higher than in the benchmark scenario under M and MST scenarios. That leads to decreases in the consumption of corn ethanol and cellulosic ethanol about 0.2 B and 2.8 B liters under the mandate scenario. Under the MST scenario, the reduction in corn ethanol and cellulosic ethanol consumption would be 1 B and 2 B liters. That is because cellulosic ethanol is competitive compared to corn ethanol due to the provision of volumetric subsidy. Again, the effects on gasoline consumption, VMT and GHG emissions are small (less than 1%) due to a small share of ethanol imports in total biofuel consumption.

7.3 Conclusions and Discussion

The promotion of biofuel policies, such as mandates and subsides, is to reduce the dependence on foreign oil reserves and mitigate GHG emissions. Concerns about the adverse effects of biofuel mandate on food prices have led to a call for the elimination of import tariffs to increase sugarcane ethanol imports from Brazil. This chapter extends the framework developed in chapter 6 to examine the economic viability of biofuel feedstocks under alternative policy scenarios, and investigate to what extent the import tariffs affect food and feed prices. It creates a business as usual scenario that does not include any biofuel and climate policies, and analyzes the differential effects by incorporating one policy at a time on the mix of fuels consumption, GHG emissions and social welfare. Implications for cropland allocation and food and fuel prices are also examined.

We find that a binding biofuel mandate would rely on corn ethanol to meet 65% of cumulative biofuel mandate over the 2007-2022 period while sugarcane ethanol imports would meet about 4.5% of the mandate. Miscanthus would meet 75% of the advanced biofuel target, and switchgrass and crop residues meet the rest of the mandates. The biofuel mandate also results in a reduction in cumulative gasoline consumption over the period of 2007-2022 by 7% and a reduction in gasoline price in 2022 by 8%. Land under corn would increase by 22%, which is met by reducing acreage under soybean, wheat and other crops and converting pasture land to corn production. Corn and soybean prices in 2022 are 24% and 21% higher than under the BAU despite the gains in crop productivity.

The provision of tax credits for biofuels make cellulosic ethanol become competitive with corn ethanol such that 75% of the cumulative biofuels over the 2007-2022 would be produced from cellulosic feedstocks. Increased production of cellulosic biofuels reduces sugarcane ethanol imports by 2.4% over the 2007-2022 period relative to the BAU. The subsidy also lowers the consumer price of miles and creates incentives for miles consumers to increase the VMT by 500 B kilometers relative to a mandate alone. GHG intensity of the blended fuel decreases due to increased share of cellulosic biofuels in total fuel consumption, and it is large enough to offset the increase in GHG emissions due to the additional VMT consumption. The total GHG emissions would now be decreased by about 5% relative to the BAU scenario over the 2007-2022 period. Corn price in 2022 decreases by 13% relative to the BAU.

The imposition of import tariffs would result in a reduction in ethanol imports by 12 B liters relative to the mandate and subsidy scenario. That would increase domestic corn ethanol and cellulosic ethanol by 5 B and 7 B liters, respectively. Since the volumetric share of ethanol imports only accounts for 2.5% in total biofuel consumption, the effects of import tariffs on food prices, GHG emissions and social welfare are not significantly different from a biofuel mandate and subsidy scenario.

This analysis emphasizes the role of technological process in sugarcane ethanol refinery. The decline in feedstock and refinery costs for sugarcane ethanol induced by learning-by-doing experience can contribute to mitigating the demand for domestically produced corn ethanol and cellulosic ethanol and alleviating the competition for cropland and the adverse impacts on food prices. Among biofuel policies considered here, a mandate alone policy would be the preferred policy because it generates the largest net social benefit for the fuel and agricultural sectors.

Tables

Table 7.1: Model Validation for 2007

	Observed	Model	Difference (%)
Land Use (M Ha)			
Total Land	123.05	121.33	-1.40
Corn	34.31	30.80	-10.24
Soybeans	28.15	26.91	-4.41
Wheat	21.52	23.61	9.72
Sorghum	2.69	2.96	10.31
Commodity Prices ($/MT)			
Corn	142.51	123.92	-13.04
Soybeans	303.69	261.80	-13.79
Wheat	197.31	213.76	8.33
Sorghum	145.07	123.31	-15.00
Fuel Sector			
Gas Prices ($/Liter)	0.72	0.72	0.00
Ethanol Prices ($/Liter)	0.61	0.60	-1.64
Gas Consumption (B Liters)	519.94	518.90	-0.20
Ethanol Consumption (B Liters)	23.51	24.76	5.30
Ethanol Import (B Liters)	1.93	1.70	-12.01
Miles Consumption (B Kms)	4863.29	4863.29	0.00

Table 7.2: Effects of Biofuel Policies on the Agricultural Sector in 2022

	BAU 2007	BAU	M	MS	MST
Land Use (M Ha)					
Total land	120.84	122.88	124.85	119.55	119.60
Corn	28.47	28.97	35.32	25.22	25.26
Soybeans	28.15	28.13	26.21	28.71	28.70
Wheat	24.66	26.17	24.27	25.42	25.40
Alfalfa	24.32	23.87	23.73	23.54	23.56
Stover			3.45	6.82	7.10
Straw			0.64	1.63	1.62
Miscanthus			6.14	11.90	11.97
Switchgrass			0.83	1.38	1.32
Crop Production (M MT)					
Corn	267.51	322.47	395.22	283.08	282.82
Soybeans	77.65	84.69	78.53	88.43	88.36
Wheat	59.50	74.65	68.76	72.62	72.63
Crop Prices ($/MT)					
Corn	108.43	108.06	134.16	93.12	93.12
Soybeans	225.15	243.46	294.35	223.53	223.53
Wheat	200.60	196.35	214.73	198.48	200.45

Table 7.3: Effects of Biofuel Policies on Fuel Sector and Emissions in 2022

	BAU 2007	BAU	M	MS	MST
Prices in 2022 ($/Km or $/Liter)					
Miles	0.080	0.087	0.087	0.081	0.081
Corn Ethanol	0.682	0.66	0.68	0.51	0.51
Cellulosic Ethanol			0.81	0.51	0.52
Sugarcane Ethanol	0.677	0.66	0.81	0.52	0.51
Gasoline	0.731	0.78	0.72	0.73	0.73
Cumulative Consumption Over 2007-2022 (B Liters or B Kms)					
Miles	82890.05	82890.05	83102.57	83601.22	83597.56
Gasoline	8922.62	8922.62	8319.29	8372.78	8372.41
Ethanol	331.42	331.42	1220.98	1221.80	1221.77
Ethanol Import	43.92	43.92	54.70	42.87	30.96
Corn	287.51	287.51	789.71	259.41	264.42
Stover			44.98	71.97	79.11
Straw			1.81	11.48	12.15
Miscanthus			314.95	803.08	803.32
Switchgrass			14.83	33.00	31.80
Cumulative Greenhouse Gas Emissions Over 2007-2022 (B MT)					
Emissions	29.374	29.374	28.303	27.815	27.815

Table 7.4: Effects of Biofuel Policies on Social Welfare (%) Relative to BAU ($ B or %)[1]

	M	MS	MST
Miles Consumers	66.86	215.46	214.40
	0.50%	*1.62%*	*1.62%*
Domestic Gasoline Producers	-67.22	-60.78	-60.82
	-5.75%	*-5.20%*	*-5.20%*
World Gasoline Producers	-141.76	-130.27	-130.35
	-15.67%	*-14.40%*	*-14.41%*
Agricultural Consumers	-62.04	-17.30	-17.80
	-3.34%	*-0.93%*	*-0.96%*
Agricultural Producers[2]	190.89	66.12	68.06
	21.39%	*7.41%*	*7.62%*
Crop Producers	208.26	39.12	38.99
	41.90%	*7.87%*	*7.84%*
Biomass Producers	18.91	29.31	31.01
Livestock Producers	-36.28	-2.31	-1.94
	-9.17%	*-0.58%*	*-0.49%*
Government Revenue ($B)	0.00	-190.11	-188.80
Externality Cost	21.99	31.75	31.73
	-3.32%	*-4.79%*	*-4.78%*
Total Welfare[3]	150.49	45.15	46.76
	0.91%	*0.27%*	*0.28%*

1. Percentage change in italics is relative to the BAU level.
2. Agricultural producers' surplus includes surplus from crop producers, biomass producers and livestock producers.
3. Total social welfare calculation does not include world gasoline producers.

Table 7.5: Sensitivity Analysis[1]

	Benchmark		Double Supply Elasticity of Ethanol		Double Growth Rate of Sugarcane Ethanol Production	
	M[2]	MST	M	MST	M	MST
Changes in Land Uses (%)						
Total Land	1.60	-2.67	2.03	-2.58	1.44	-2.86
Corn	21.91	-12.81	22.78	-12.78	21.81	-13.06
Soybeans	-6.84	2.02	-6.59	1.97	-6.78	1.93
Wheat	-7.26	-2.96	-7.15	-3.24	-7.69	-3.51
Cellulosic Feedstock Areas (M Ha)						
Stover	3.45	7.10	6.19	6.30	3.45	6.50
Straw	0.64	1.62	1.38	1.61	0.66	1.63
Miscanthus	6.14	11.97	5.13	12.08	6.13	12.02
Switchgrass	0.83	1.32	0.95	1.40	0.83	1.32
Changes in Crop Production and Prices in 2022(%)						
Corn Production	22.56	-12.30	23.26	-12.60	22.47	-12.61
Corn Price	24.15	-13.83	26.75	-10.82	28.56	-10.37
Soybeans Production	-7.28	4.33	-7.71	4.36	-7.30	4.33
Soybeans Price	20.91	-8.18	26.48	-5.63	24.27	-5.63
Wheat Production	-7.88	-2.70	-7.39	-3.08	-7.68	-2.49
Wheat Price	9.36	2.09	10.04	3.40	9.92	2.27
Changes in Fuel Prices in 2022 and Cumulative Consumption of Fuels and Mile Consumption (%)						
Gasoline Price	-7.87	-7.05	-7.80	-7.05	-7.83	-7.05
Corn Ethanol price	3.02	-22.60	3.44	-21.61	4.32	-21.26
Cellulosic Ethanol Price	0.81	0.52	0.78	0.52	0.79	0.51
Domestic Gasoline Supply	-2.50	-2.26	-2.50	-2.24	-2.50	-2.26
World Gasoline Supply	-8.73	-7.97	-8.76	-7.94	-8.73	-7.96
Corn Ethanol	174.68	-8.03	183.76	-6.85	176.48	-7.67
Cellulosic Ethanol	376.57	926.38	351.31	933.59	373.79	924.34
Ethanol Import	24.55	-29.49	49.41	-46.21	23.19	-27.88
Mile Consumption	0.26	0.85	0.22	0.86	0.25	0.85
Changes in GHG Emissions and Social Welfare (%)						
GHGs	-3.65	-5.31	-3.56	-5.31	-3.65	-5.31
Social Welfare	0.91	0.28	0.87	0.31	0.87	0.27

1. Percentage change is calculated relative to baseline (BAU) results where baselines change with different parameters;
2. M denotes biofue mandate alone policy, and MST represents the policy of consumption mandates with subsidies and import tariffs.

Chapter 8 Conclusions and Caveats

8.1 Summary

Biofuels have been considered as a central strategy to reduce the dependence on foreign oils and mitigate GHG emissions in the U.S. Policy initiatives, such as biofuel mandates and subsidies, have switched the focus from corn ethanol to second-generation biofuels made from non-food based feedstocks to mitigate the competition for cropland and reduce the adverse impacts on food/feed prices. This dissertation 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 under alternative bioufel and climate policies. It analyzes the differential effects under alternative policies on biofuel production, the mix of biofuels from corn and alternative cellulosic feedstocks, and implications for GHG emissions and social welfare.

The theoretical model developed in chapter 3 analyzes the mechanisms by which biofuel policies affect fuel choices and consumption and differ from a carbon tax policy. It also indentifies several import parameters that potentially could affect market outcomes. The numerical model in chapter 4 then expands the simplified representation of agricultural and fuel sectors by developing a dynamic, multi-market, partial equilibrium Biofuel and Environmental Policy Analysis Model (BEPAM). Chapter 5 describes the sources of data and parameters used in this study.

In chapter 6 we analyze welfare costs of meeting biofuel mandates and implications for food/feed prices and GHG emissions, and compare results with a carbon tax policy. We find that a tax of \$30 per ton of CO_2e would induce additional production of corn ethanol ranging from 16% to 47% and increase corn prices by 6% to 12% and would not create incentives for production of cellulosic ethanol. The tax would reduce GHG emissions by 3% to 4% compared to the BAU scenario.

While a biofuel mandate (without any subsidies) would use corn ethanol to the maximum level allowed, miscanthus would meet 90% of the advanced biofuel targets with crop residues and switchgrass meeting the rest. The mandate leads to an 20% increase in corn acreage met in part by reducing acreage under soybean and other crops and in part by converting pasture land to corn. The corn price in 2022 is 26% higher than in the BAU despite gains in corn productivity over the 2007-2022 period. The biofuel mandate also results in a reduction in gasoline consumption over the period of 2007-2022 by 7% and reduction in gasoline price in 2022 by 8% compared to the BAU level. Overall reduction in cumulative GHG emissions is about 1% more than the reduction achieved by the carbon tax policy.

The existing volumetric subsidies for cellulosic biofuels make cellulosic biofuels competitive with corn ethanol and shift the mix of biofuels such that 87% of the cumulative biofuels over the 2007-2022 would now be produced from cellulosic feedstocks. This reduces corn price in 2022 by 10-14% relative to the BAU while the GHG emissions reduction ranges from 5% to 9% depending on the fuel market parameters.

To meet the cellulosic biofuel mandates, a mix of feedstocks (corn stover, wheat straw, switchgrass and miscanthus) is used, where the mix differs over time. The production of energy crops increases over time with miscanthus playing a more important role in meeting the cellulosic biofuel target, accounting for 91% and 90% of the total cellulosic ethanol produced for 2007- 2022 under the mandate and the mandate and subsidy scenarios, respectively. Corn stover comes primarily from the plain states Nebraska, South Dakotas and Kansas. Wheat straw is collected mainly in the central and northern plains and western mountain states (Kansas, Nebraska, North and South Dakotas, Montana, Idaho and Washington). Production of miscanthus is more concentrated in the Great Plains (South Dakota, Nebraska, Kansas and Oklahoma), and in the Midwest and along lower reaches of the Mississippi river. Switchgrass, though not as competitive as miscanthus in terms of yields and costs of production in most parts of the country, is still produced in a significant amount in northern and central Texas and Wisconsin.

Since gasoline supply from the rest of the world accounts for a large share of total gasoline consumption in the U.S, world gasoline producers would bear most of surplus loss due to the displacement of biofuels for gasoline. Domestic social welfare would achieve the highest level under a mandate (without any subsidies) relative to a carbon tax and the biofuel mandate accompanied with biofuel subsidies. The net social welfare gain under a mandate alone ranges from \$56 B to \$188 B relative to the BAU across the various parameter assumptions considered here.

In chapter 7, we incorporate ethanol imports from Brazil and CBI countries to investigate the effects of import tariffs on land use and food production and price. We also examine the mix of corn ethanol, domestic cellulosic ethanol and sugarcane ethanol under alternative policy scenarios. The implications for GHG emissions and social welfare are also examined. We find that a binding biofuel mandate would rely on corn ethanol to meet 65% of cumulative biofuel mandate over the 2007-2022 period while sugarcane ethanol imports would meet about 4.5% of the mandate. Miscanthus would meet 75% of the advanced biofuel target, and switchgrass and crop residues meet the rest of the mandates. The biofuel mandate also results in a reduction in cumulative gasoline consumption over the period of 2007-2022 by 7% and a reduction in gasoline price in 2022 by 8%. Land under corn would increase by 22%, which is met by reducing acreage under soybean, wheat and other crops and converting pasture land to corn production. Corn and soybean prices in 2022 are 24% and 21% higher than under the BAU despite the gains in crop productivity.

The provision of tax credits for biofuels make cellulosic ethanol competitive with corn ethanol such that 75% of the cumulative biofuels over the 2007-2022 would be produced from cellulosic feedstocks. That reduces sugarcane ethanol imports by 2.4% over the 2007-2022 period relative to the BAU. The subsidy also lowers the consumer price of miles and creates incentives for miles consumers to increase the VMT by 500 B kilometers relative to a mandate alone. GHG intensity of the blended fuel decreases due to increased share of cellulosic biofuels in total fuel consumption, and it is large enough to offset the increase in GHG emissions due to the additional VMT consumption. The total GHG emissions would now be decreased by about 5% relative to the BAU scenario over the 2007- 2022 period. Corn price in 2022 decreases by 13% relative to the BAU.

The imposition of import tariffs would result in a reduction in ethanol imports by 12 B liters relative to the mandate and subsidy scenario. That would increase domestic corn ethanol and cellulosic ethanol by 5 B and 7 B liters, respectively. Since the volumetric share of ethanol imports only accounts for 2.5% in total biofuel consumption, the effects of import tariffs on food prices, GHG emissions and social welfare are not significantly different from a biofuel mandate and subsidy scenario.

8.2 Caveats

This dissertation develops a dynamic multi-equilibrium land use model to analyze the effects of biofuel policies in the U.S. The proposed framework in this study can be used to make informed predictions on how energy and agricultural policies may affect the cropland allocation and food prices and the consequences on GHG emissions and social welfare.

We now discuss a few caveats. The analysis includes only a few feedstocks for cellulosic biofuels. Forest-derived biomass resource is not included. Uncollected forest residues produced by logging and land clearing operations and unutilized residues from wood processing mills and unutilized urban wood, can be potentially used for the production of cellulosic biofuels. If forest residues can be collected in an economically viable way, the competition for cropland and the adverse effects on food prices due to RFS mandates can be expected to be mitigated.

We assume fixed export demand for U.S. crop and livestock commodities and fixed import supply for sugar and sugarcane ethanol. The expansion of biofuel production in the U.S. is expected to reduce the supply of crop and livestock commodities to the rest of the world, such as corn, soybeans, wheat, pork and beef. Foreign consumers may respond to this reduction by seeking substitutes or increasing their domestic supply. That in turn may affect the supply of sugar and sugarcane ethanol to the U.S. Thus, both export demand and import supply curves to the U.S. may be affected accordingly. Current analysis ignores this interaction effect on export demand and import supply curves due to U.S. biofuel policies.

Future research should also consider other demands for cellulosic feedstocks apart from biofuels, such as power generation co-firing biomass with coal. Many states in the U.S. have established the Renewable Portfolio Standards (RFS) that requires electric utilities to generate a minimum percentage of their electricity from renewable sources. Since about one-third of the total GHG emissions are generated by coal-based electricity production (USDOE/EIA 2006), co-firing biomass with coal can be expected to significantly reduce overall GHG emissions.

Bibliography

Adams, D., R. Alig, B. McCarl, and B. C. Murray. 2005. *FASOMGHG Conceptual Structure, and Specification: Documentation*. http://agecon2.tamu.edu/people/faculty/mccarl-bruce/FASOM.html.

Ando, A. W., M. Khanna, and F. Taheripour. 2010. "Market and Social Welfare Effect of the Renewable Fuels Standard. In: M. Khanna., J. Scheffran and D. Zilberman, eds., Handbook of Bioenergy Economics and Policy."

Argonne National Laboratory. 2009. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*. Chicago, Illinois.

Babcock, B. A., D. J. Hayes, and J. D. Lawrence. 2008. *Using Distillers Grains in the U.S. and International Livestock and Poultry Industries.* Iowa State University: Midwest Agribusiness Trade Research and Information Center.

Baker, J. S., B. A. McCarl, B. C. Murray, S. K. Rose, R. J. Alig, D. Adams, G. Latta, R. Beach, and A. Daigneault. 2009. *The Effects of Low-Carbon Policies on Net Farm Income*. Durham, NC, Nicholas Institute for Environmental Policy Solutions, Duke University, pp. 1-16.

Birur, D., T. Hertel, and W. Tyner. 2008. *The Biofuels Boom: Implications for World Food Markets*. Sponsored by the Dutch Ministry of Agriculture, January 9, 2008.

Brechbill, S., W. Tyner, and K. Ileleji. 2008. *The Economics of Biomass Collection and Transportation and Its Supply to Indiana Cellulosic and Electric Utility Facilities.* In: Proceedings Q8 Risk, Infrastructure and Industry Evolution Conference, June 24–25, 2008, Berkeley, CA (eds English BC, Menard RJ, Jensen K).

Bredahl, M. E., W. H. Meyers, and K. J. Collins. 1979. "The Elasticity of Foreign Demand for U.S. Agricultural Products: The Importance of the Price Transmission Elasticity." *American Journal of Agricultural Economics* 61 (1): 58-63.

Brummer, E., C. Burras, M. Duffy, and K. Moore. 2000. *Switchgrass production in Iowa: economic analysis, soil suitability, and varietal performance.*

Carley, D. H., and S. M. Fletcher. 1989. *Analysis of the Impact of Alternative Government Policies on Peanut Farmers*. in Experiment Station Special Publiccation 62, University of Georgia.

Caswell, M., and D. Zilberman. 1986. "The Effects of Well Depth and Land Quality on the Choice of Irrigation Technology." *American Journal of Agricultural Economics* 68 (4): 798-811.

Christian, D. G., A. B. Riche, and N. E. Yates. 2008. "Growth, Yield and Mineral Content of Miscanthus × Giganteus Grown As A Biofuel for 14 Successive Harvests." *Industrial Crops and Products* 28 (3): 320-327.

Clifton-Brown J, C. Y-C, and H. TR. 2008. *Miscanthus: Genetic Resources and Breeding Potential to Enhance Bioenergy Production.* In: Genetic Improvement of Bioenergy Crops (ed.Vermerris W), pp. 273–294. Springer Science1Business Media,LLC, New York.

Clifton-Brown, J., J. Brewer, and M. Jones. 2007. "Carbon Mitigation by the Energy Crop Miscanthus." *Global Change Biology* 13 (11): 2296-2307.

de Gorter, H., and D. R. Just. 2007. *The Law of Unintended Consequences: How the U.S. Biofuel Tax Credit with a Mandate Subsidizes Oil Consumption and Has No Impact on Ethanol Consumption*. Department of Applied Economics and Management Working Paper #

2007-20, Cornell University. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1024525.

de Gorter, H., and D. R. Just. 2008. "The Economics of the U.S. Ethanol Import Tariff with a Blend Mandate and Tax Credit." *Journal of Agricultural & Food Industrial Organization* 6: 1-21.

de Gorter, H., and D. R. Just. 2009. "The Welfare Economics of a Biofuel Tax Credit and the Interaction Effects with Price Contingent Farm Subsidies." *American Journal of Agricultural Economics* 91 (2): 477-488.

de Gorter, H., and D. R. Just. 2010. "The Social Costs and Benefits of Biofuels: The Intersection of Environmental, Energy and Agricultural Policy." *Applied Economic Perspectives and Policy* 32 (1): 4-32.

DEFRA. 2001. *A Review of the Potential of Giant Grasses for UK Agriculture.* Research and development—final project report NF0419. Accessed from /http://www2.defra.gov.uk/research/project_data/More.asp?I=NF0419&M=CFO&V=COSARS.

Dhungana, B. R. 2007. "Economic Modeling of Bioenergy Crop Production and Carbon Emission Reduction in Illinois." PhD Dissertation, University of Illinois.

Duffy, M. 2007. *Estimated Costs for Production, Storage and Transportation of Switchgrass.*

Duffy, M., and V. Nanhou. 2001. *Costs of Producing Switchgrass for Biomass in Iowa.* Accessed from /http://www.extension.iastate.edu/Publications/PM1866.pdfS.

Dumortier, J., D. J. Hayes, M. Carriquiry, F. Dong, X. Du, A. Elobeid, J. F. Fabiosa, and S. Tokgoz. 2009. *Sensitivity of Carbon Emission Estimates from Indirect Land-Use Change*. Ames, Iowa, Center for Agricultural and Rural Development, Iowa State University, pp. 1-15.

EIA. 2010. *Annual Energy Outlook 2010.* U.S. Energy Information Administration.

EIA. 2010. *How Dependent Are We on Foreign Oil?*

EISA. 2007. *Energy Independence and Security Act*. Available online at http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf.

Ellinger, P. 2008. *Ethanol Plant Simulator*. Urbana, Illinois, Dept. Agr Econ, University of Illinois at Urbana-Champaign.

Elobeid, A., and A. Tokgoz. 2008. "Removing Distortions in the U.S. Ethanol Market: What Does It Imply for the United States and Brazil?" *American Journal of Agricultural Economics* 90 (4): 918-932.

Elobeid, A. E., S. Tokgoz, D. J. Hayes, B. A. Babcock, and C. E. Hart. 2007. "the Long-Run Impact of Corn-Based Ethanol on Grain, Oilseed, and Livestock sectors with Implications for Biotech Crops." *AgBioForum* 10 (1): 11-18.

English, B., D. G. Ugarte, R. Menard, and T. West. 2008. *Economic and Environmental Impacts of Biofuel Expansion: the Role of Cellulosic Ethanol*. Atlanta, GA.

EPA. 2009. *Draft Regulatory Impact Analysis: Changes to Renewable Fuel Standard Program.*

EPA. 2010. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. U.S. Environmental Protection Agency, Available on line at http://www.epa.gov/otaq/fuels/renewablefuels/index.htm.

Fabiosa, J. F., J. C. Beghin, F. Dong, A. Elobeid, S. Tokgoz, and T.-H. Yu. 2009. *Land Allocation Effects of the Global Ethanol Surge: Predictions from the Internationsl FAPRI*

Model. Ames, Iowa, Center for Agricultural and Rural Development, Iowa State University, pp. 1-21.

FAPRI. 2009. *Elasticity Database*.

Fargione, J., J. Hill, D. Tilman, S. Polasky, and P. Hawthorne. 2008. "Land Clearing and the Biofuel Carbon Debt." *Science* 319 (5867): 1235-1238.

Ferris, J., and S. Joshi 2009. *Prospects for Ethanol and Biodiesel, 2008 to 2017 and Impacts on Agriculture and Food.* ed. M. Khanna, J. Scheffran, and D. Zilberman, Springer.

Fortenbery, T. R., and H. Park. 2008. *The Effect of Ethanol Production on the U.S. National Corn Price*. Staff Paper No. 523. Department of Agricultural & Applied Economics, University of Wisconsin-Madison.

Gallagher, P. W., H. Shapouri, J. Price, G. Schamel, and H. Brubaker. 2003. "Some Long-run Effects of Growing Markets and Renewable Fuel Standards on Additives Markets and the US Ethanol Industry." *Journal of Policy Modeling* 25 (6-7): 585-608.

Gao, X. M., E. J. Wailes, and G. L. Cramer. 1995. "Double-hurdle Model with Bivariate Normal Errors: An Application to U.S. Rice Demand." *Journal of Agricultural and Applied Economics* 27 (2): 363-376.

Gardner, B. 2007. "Fuel Ethanol Subsidies and Farm Price Support." *Journal of Agricultural & Food Industrial Organization* 5: 1-20.

Graham, R. L., R. Nelson, and J. Sheehan. 2007. "Current and Potential U.S. Corn Stover Supplies." *Agronomy Journal* 99: 1-11.

Greene, D. L., and N. I. Tishchishyna. 2000. *Costs of Oil Dependence: A 2000 Update.*

Gunderson, A. C., E. B. Davis, and I. H. Jager. 2008. *Exploring Potential U.S.Switchgrass Production for Lignocellulosic Ethanol.* ORNL/TM-2007/183. Oak Ridge, TN: Oak Ridge National Laboratory.

Hayes, D., B. Babcock, J. Fabiosa, S. Tokgoz, A. Elobeid, and T.-H. Yu. 2009. "Biofuels: Potential Production Capacity, Effects on Grain and Livestock Sectors, and Implications for Food Prices and Consumers." *Journal of Agricultural and Applied Economics* 41 (2): 1-27.

Heaton, E., F. Dohleman, and S. Long. 2008. "Meeting US Biofuel Goals with Less Land: the Potential of Miscanthus." *Global Change Biology* 14: 2000-2014.

Heaton, E. A., F. G. Dohleman, and S. P. Long. 2008. "Meeting US biofuel goals with less land: the potential of Micanthus." *Global Change Biology* 14: 2000-2014.

Hertel, T. W., W. E. Tyner, and D. K. Birur. 2010. "The Global Impacts of Biofuel Mandates." *The Energy Journal* 31 (1): 75-100.

Hertel, W. T., W. E. Tyner, and D. K. Birur. 2008. *Biofuels for all? Understanding the Global Impacts of Multinational Mandates*. GTAP Working Paper No.51.

Hettinga, W. G., H. M. Junginger, S. C. Dekker, M. Hoogwijk, A. J. McAloon, and K. B. Hicks. 2009. "Understanding the Reductions in US Corn Ethanol Production Costs: An Experience Curve Approach." *Energy Journal* 37: 190-203.

Huang, H., and M. Khanna. 2010. *An Econometric Analysis of U.S. Crop Yields and Acreages in the Face of Climate Change. .*

Jain, A., M. Khanna, M. Erickson, and H. Huang. 2009. "An Integrated Bio-geochemical and Economic Analysis of Bioenergy Crops in the Midwestern United States." *BioEnergy Research* (in review):

Jain, A., M. Khanna, M. Erickson, and H. Huang. 2010. "An Integrated Biogeochemical and Economic Analysis of Bioenergy Crops in the Midwestern United States." *GCB Bioenergy*: In Press.

Khanna, M. 2008. "Cellulosic Biofuels: Are They Economically Viable and Environmentally Sustainable?" *Choices* 23 (3): 16-21.

Khanna, M., A. W. Ando, and F. Taheripour. 2008. "Welfare Effects and Unintended Consequences of Ethanol Subsidies." *Review of Agricultural Economics* 30 (3): 411-421.

Khanna, M., B. Dhungana, and J. Clifton-Brown. 2008. "Costs of Producing Miscanthus and Switchgrass for Bioenergy in Illinois." *Biomass and Bioenergy* 32 (6): 482-493.

Krutilla, K. 1991. "Environmental Regulation in An Open Economy." *Journal of Environmental Economics and Management* 20 (2): 127-142.

Lasco, C., and M. Khanna. 2009. *US-Brazil Trade in Biofuels: Determinants, Constraints and Implications for Trade Policy. In: M. Khanna., J. Scheffran and D. Zilberman, eds., Handbook of Bioenergy Economics and Policy.*

Lasco, C., M. Khanna, J. Barton, E. Giuliani, and W. Amaral. 2009. *A Comparison of the Cost of Production of Sugarcane Ethanol in Brazil Relative to Corn Ethanol in the United States*. University of Illinois at Urbana-Champaign, Working Paper.

Lemus, R., and D. L. Parrish. 2009. "Herbaceous Crops with Potential for Biofuel Production in the USA." *CABI Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 4: 1-23.

Lewandowski, I., J. M. O. Scurlock, E. Lindvall, and M. Christou. 2003. "The Development and Current Status of Perennial Rhizomatous Grasses as Energy Crops in the US and Europe." *Biomass and Bioenergy* 25 (4): 335-361.

Lewandowski, I., J. M. O. Scurlock, E. Lindvall, and M. Christou. 2003. "The development and current status of potential rhizomatous grasses as energy crops in the US and Europe." *Biomass and Bioenergy* 25 (4): 335-361.

Macedo, I. C., J. E. A. Seabra, and J. E. A. R. Silva. 2008. "Green House Gases Emissions in the Production and Use of Ethanol from Sugarcane in Brazil: The 2005/2006 Averages and a Prediction for 2020." *Biomass and Bioenergy* 32 (7): 582-595.

Malcolm, S. 2008. *Weaning Off Corn: Crop Residues and the Transition to Cellulosic Ethanol*. St. Louis, MO.

McCarl, B. A., and U. A. Schneider. 2001. "Greenhouse Gas Mitigation in U.S. Agriculture and Forestry." *Science* 294: 2481-2482.

McCarl, B. A., and T. H. Spreen. 1980. "Price Endogenous Mathematical Programming as a Tool for Policy Analysis." *American Journal of Agricultural Economics* 62: 87-102.

Mooney, D. F., R. K. Robertsa, B. C. Englisha, D. D. Tylerb, and J. A. Larsona. 2009. "Yield and Breakeven Price of 'Alamo' Switchgrass for Biofuels in Tennessee." *Agronomy Journal* 101: 1234-1242.

Önal, H., and B. A. McCarl. 1991. "Exact Aggregation in Mathematical Programming Sector Models." *Canadian Journal of Agricultural Economics* 39: 319-334.

Perrin, R., K. Vogel, M. Schmer, and R. Mitchell. 2008. "Farm-Scale Production Cost of Switchgrass for Biomass." *BioEnergy Research* 1: 91-97.

Piggott, N. E., and M. K. Wohlgenant. 2002. "Price Elasticities, Joint Products, and International Trade." *Australian Journal of Agricultural and Resource Economics* 46 (4): 487-500.

Qin, X., T. Mohan, M. El-Halwagi, G. Cornforth, and B. A. McCarl. 2006. "Switchgrass as An Alternate Feedstock for Power Generation: An Integrated Environmental, Energy and

Economic Life-cycle Assessment " *Clean Technologies and Environmental Policy* 8: 233-249.

Rajagopal, D., S. E. Sexton, D. Roland-Holst, and D. Zilberman. 2007. "Challenge of Biofuel: Filling the Tank without Emptying the Stomach?" *Environmental Research Letters* 2: 1-9.

Reilly, J., A. Gurgel, and S. Paltsev. 2009. *Biofuels and Land Use Change*. ed. M. Khanna St. Louis, MO, Farm Foundation.

Runge, C. F., and B. Senauer. 2007. "How Biofuels Could Starve the Poor." *Foreign Affairs* 86 (3): 41-53.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." *Science* 319 (5867): 1238-1240.

Searcy, E., P. Flynn, E. Ghafoori, and A. Kumar. 2007. "The Relative Cost of Biomass Energy Transport." *Applied Biochemistry and Biotechnology* 137-140: 639-652.

Semere, T., and F. M. Slater. 2007. "Invertebrate Populations in Miscanthus (Miscanthus×giganteus) and Reed Canary-Grass (Phalaris Arundinacea) Fields." *Biomass and Bioenergy* 31 (1): 30-39.

Sheehan, J., A. Aden, K. Paustian, K. Killian, J. Brenner, M. Walsh, and R. Nelson. 2003. "Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol." *Journal of Industrial Ecology* 7: 117-146.

Takayama, T., and G. G. Judge. 1971. *Spatial and Temporal Price and Allocation Models.* Amsterdam: North Holland Publ. Co.

Tokgoz, S., A. Elobeid, J. F. Fabiosa, D. Hayes, B. A. Babcock, T.-H. Yu, F. Dong, C. E. Hart, and J. C. Beghin. 2007. *Emerging Biofuels: Outlook of Effects on U.S. Grain, Oilseed, and Livestock Markets.*

Tyner, W., and F. Taheripour. 2008. "Policy Options for Integrated Energy and Agricultural Markets." *Review of Agricultural Economics* 30 (3): 387-396.

Tyner, W. E. 2008. "The US Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospects." *BioScience* 58 (7): 646-653.

Tyner, W. E., and F. Taheripour. 2007. "Renewable Energy Policy Alternatives for the Future." *American Journal of Agricultural Economics* 89 (5): 1303-1310.

Ugarte, D. d. l. T., B. C. English, C. Hellwinckel, T. O. West, K. L. Jensen, C. D. Clark, and R. J. Menard. 2009. *Analysis of the Implications of Climate Change and Energy Legislation to the Agricultural Sector*. Knoxville, Tennessee., Department of Agricultural Economics, Institute of Agriculture, The University of Tennessee.

Ugarte, D. G., M. E. Walsh, H. Shapouri, and S. P. Slinsky. 2003. *The Economic Impacts of Bioenergy Crop Production on U.S. Agriculture.* U.S. Department of Agriculture.

USDA. 2009. *A Preliminary Analysis of the Effects of HR 2354 on U.S. Agriculture.*

USDA/ERS. 1997. *General Crop Management Practices*. From http://www.ers.usda.gov/publications/sb969/sb969e.pdf.

USDA/ERS. 2009. *Commodity and Food Elasticities: Demand Elasticities from Literature*. From http://www.ers.usda.gov/Data/Elasticities/query.aspx

USDA/NASS. 2009. http://quickstats.nass.usda.gov/.

USDA/NASS. 2009. *U.S. & All States County Data - Crops.*

USDOE/EIA. 2006. *Emissions of Greenhouse Gases in the United States 2005*. U.S. Department of Energy, Energy Information Administration, November Edition. Retrieved on September 1, 2007, from http://www.eia.doe.gov/oiaf/1605/ggrpt/index.html.

van den Wall Bake, J. D., M. Junginger, A. Faaij, T. Poot, and A. Walter. 2009. "Explaining the Experience Curve: Cost Reductions of Brazilian Ethanol from Sugarcane." *Biomass and Bioenergy* 33 (4): 644-658.

Vedenov, D., and M. Wetzstein. 2008. "Toward an Optimal U.S. Ethanol Fuel Subsidy." *Energy Economics* 30 (5): 2073-2090.

Von Lampe, M. 2006. *Agricultural Market Impacts of Future Growth in the Production of Biofuels. Working Party on Agricultural Policies and Markets, AGR/CA/APM (2005) 24.*

Wallace, R., K. Ibsen, A. McAloon, and W. Yee. 2005. *Feasibility Study for Co-Locating and Integrating Ethanol Production Plants from Corn Starch and Lignocellulogic Feedstocks.*

Walsh, M. E., D. G. d. l. T. Ugarte, H. Shapouri, and S. P. Slinsky. 2003. "Bioenergy Crop Production in the United States: Potential Quantities, Land Use Changes, and Economic Impacts on the Agricultural Sector." Environmental and Resource Economics 24 (4): 313-333.

Wilcke, W., and G. Wyatt. 2002. *Grain Storage Tips*. Twin Cities, MN, The University of Minnesota Extension Service, the University of Minnesota.

Wortmann, C. S., R. N. Klein, W. W. Wilhelm, and C. Shapiro. 2008. *Harvesting Crop Residues.* University of Nebraska

Wu, M. 2008. *Analysis of the Efficiency of the U.S. Ethanol Industry 2007.*

Wu, M., M. Wang, and H. Huo. 2006. *Fuel-Cycle assessment of Selected Bioethanol Production Pathways in the United States.* Argonne National Laboratory Report, ANL/ESD/06-7.

Appendix A: Comparative Static Analysis of a Carbon Tax

Totally differentiating (3.2) to (3.4) and $f + e \le \overline{L}$, we get

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

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

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

Where

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

From the first order conditions (3.3) and (3.4), we have $m_e = \frac{p_e}{P(m)}$ and $m_g = \frac{p_g}{P(m)}$. Let us define $s_e = \frac{m_e e}{m}$ and $s_g = \frac{m_g g}{m}$ and refer to them as the cost shares of fuels on miles expenditure.

$$\frac{\partial^2 U(m)}{\partial e^2} = U^{"}_{mm} m_e^2 + U^{'}_{m} m_{ee} = \frac{dP(m)}{dm} m_e^2 + P(m) m_{ee} = \frac{P(m)m}{e^2}\left(\frac{1}{\varepsilon_m^d}.\frac{m_e^2 e^2}{m^2} - EMP_e.\frac{m_e e}{m}\right)$$

$$= \frac{I_m s_e}{e^2}\left(\frac{s_e}{\varepsilon_m^d} - EMP_e\right),$$

$$\frac{\partial^2 U(m)}{\partial g^2} = U^{"}_{mm} m_g^2 + U^{'}_{m} m_{gg} = \frac{dP(m)}{dm} m_g^2 + P(m) m_{gg} = \frac{P(m)m}{g^2}\left(\frac{1}{\varepsilon_m^d}.\frac{m_g^2 g^2}{m^2} - EMP_g.\frac{m_g g}{m}\right)$$

$$= \frac{I_m s_g}{g^2}\left(\frac{s_g}{\varepsilon_m^d} - EMP_g\right),$$

$$\frac{\partial^2 U(m)}{\partial e \partial g} = U^{"}_{mm} m_e m_g + U^{'}_{m} m_{ge} = \frac{dP(m)}{dm} m_e m_g + P(m) m_{ge} = \frac{I_m s_e s_g}{ge}\left(\frac{1}{\varepsilon_m^d} + \frac{1}{\sigma}\right), \text{and}$$

$$\sigma = \frac{m_g m_e}{m_{ge} m};\ m_{gg} m_{ee} = m_{ge} m_{eg} \Leftrightarrow EMP_g EMP_e = \frac{s_e s_g}{\sigma^2}. \tag{A1}$$

The first term of *H* is always positive according to our assumptions that utility functions are strictly concave and cost functions are convex. The rest of the terms

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

$$= -\frac{\partial^2 U(m)}{\partial g^2}.c^{"}(e) - \frac{\partial^2 U(m)}{\partial e^2}.c^{"}(g) + c^{"}(g).c^{"}(e) + \frac{\partial^2 U(m)}{\partial g^2}.\frac{\partial^2 U(m)}{\partial e^2} - \left(\frac{\partial^2 U(m)}{\partial g \partial e}\right)^2$$

$$= \Omega + \frac{\partial^2 U(m)}{\partial g^2}.\frac{\partial^2 U(m)}{\partial e^2} - \left(\frac{\partial^2 U(m)}{\partial g \partial e}\right)^2$$

$$= \Omega + (U^{'}_{m})^2 (m_{gg} m_{ee} - m_{ge} m_{eg}) + U^{"}_{mm} U^{'}_{m} (m_{gg} m_e^2 + m_{ee} m_g^2 - 2 m_g m_e m_{ge})$$

$$= \Omega + U^{"}_{mm} U^{'}_{m} (m_{gg} m_e^2 + m_{ee} m_g^2 - 2 m_g m_e m_{ge}) > 0 \tag{A2}$$

Where $\Omega = -\frac{\partial^2 U(m)}{\partial g^2}.c^{"}(e) - \frac{\partial^2 U(m)}{\partial e^2}.c^{"}(g) + c^{"}(g).c^{"}(e)$ is positive. So *H* is always positive.

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

$$=\frac{1}{H}\cdot\{\delta_g[\frac{p_f}{\varepsilon_f^d f}-\frac{c^{'}(f)}{\varepsilon_f^s f}+\frac{I_m s_e}{e^2}(\frac{s_e}{\varepsilon_m^d}-EMP_g)-\frac{c^{'}(e)}{\varepsilon_e^s e}]-\delta_e\frac{I_m s_e s_g}{ge}(\frac{1}{\varepsilon_m^d}+\frac{1}{\sigma})\}$$

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

The first two terms in brackets in above equation are negative. The last term

$\delta_g g s_e-\delta_e e s_g>\delta_e(g s_e-e s_g)$ because of $\delta_g > \delta_e$. Substituting $s_e=\frac{m_e e}{m}$ and $s_g=\frac{m_g g}{m}$ into the rhs

of this expression yields: $\delta_e(g s_e-e s_g)=\delta_e(g\frac{m_e e}{m}-e\frac{m_g g}{m})=\frac{\delta_e g e}{m}(m_e-m_g)>0$

So $\frac{dg}{dt}<0$ (A3)

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

$$\delta_e[\frac{\partial^2 U(m)}{\partial g^2}-c^{"}(g)]-\delta_g\frac{\partial^2 U(m)}{\partial e\partial g}$$

$$=\delta_e.\frac{I_m s_g}{g^2}(\frac{s_g}{\varepsilon_m^d}-EMP_g)-\delta_g.\frac{I_m s_e s_g}{ge}(\frac{1}{\varepsilon_m^d}+\frac{1}{\sigma})-\delta_e\frac{c^{'}(g)}{\varepsilon_g^s g}$$

$$=\frac{I_m}{g^2 e}[\delta_e s_g e(\frac{s_g}{\varepsilon_m^d}-EMP_g)-\delta_g s_e s_g g(\frac{1}{\varepsilon_m^d}+\frac{1}{\sigma})]-\delta_e\frac{c^{'}(g)}{\varepsilon_g^s g}$$

Substituting (A1) into above expression yields

$$\begin{aligned}\frac{de}{dt} &= \frac{1}{H}\{\frac{I_m s_g}{g^2 e}.\frac{1}{\varepsilon_m^d}(\delta_e s_g e - \delta_g s_e g)\} - \frac{1}{H}\{\frac{I_m s_g s_e}{g^2 e\sigma}(\frac{\delta_e s_g e}{\sigma EMP_e} + \delta_g g) + \delta_e \frac{p_g}{\varepsilon_g^s g}\} \\ &= \frac{1}{H}\{\frac{I_m s_g}{g^2 e}.\frac{1}{\varepsilon_m^d}(\delta_e \frac{(p_g + \delta_g t)ge}{I_m} - \delta_g \frac{(c^{'}(e) + \delta_e t)ge}{I_m})\} - \frac{1}{H}\{\frac{I_m s_g s_e}{g^2 e\sigma}(\frac{\delta_e s_g e}{\sigma EMP_e} + \delta_g g) + \delta_e \frac{p_g}{\varepsilon_g^s g}\} \\ &= \frac{1}{H}\{\frac{s_g}{g}.\frac{1}{\varepsilon_m^d}(\delta_e (p_g + \delta_g t) - \delta_g (c^{'}(e) + \delta_e t))\} - \frac{1}{H}\{\frac{I_m s_g s_e}{g^2 e\sigma}(\frac{\delta_e s_g e}{\sigma EMP_e} + \delta_g g) + \delta_e \frac{p_g}{\varepsilon_g^s g}\}\end{aligned}$$

(A4)

It is straightforward to show $\frac{df}{dt} = -\frac{de}{dt}$ (A5)

and $\frac{d\lambda}{dt} = (\frac{c^{'}(f)}{\varepsilon_f^s f} - \frac{p_f}{\varepsilon_f^d f})\frac{de}{dt}$ (A6)

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

(A7)

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

(A8)

$$\begin{aligned}
\frac{dm}{dt} &= m_g \frac{dg}{dt} + m_e \frac{de}{dt} \\
&= \frac{m_g}{H}.\{\delta_g[\frac{p_f}{\varepsilon_f^d f} - \frac{c^{'}(f)}{\varepsilon_f^s f} - \frac{I_m s_e}{e^2} EMP_g - \frac{c^{'}(e)}{\varepsilon_e^s e}] - \delta_e \frac{I_m s_e s_g}{ge\sigma} + \frac{I_m s_e}{ge^2 \varepsilon_m^d}(\delta_g g s_e - \delta_e e s_g)\} \\
&+ \frac{m_e}{H}\{\delta_e.\frac{I_m s_g}{g^2}(\frac{s_g}{\varepsilon_m^d} - EMP_g) - \delta_g.\frac{I_m s_e s_g}{ge}(\frac{1}{\varepsilon_m^d} + \frac{1}{\sigma}) - \delta_e \frac{c^{'}(g)}{\varepsilon_g^s g}\} \\
&= \frac{1}{H}\{m_g \delta_g [\frac{p_f}{\varepsilon_f^d f} - \frac{c^{'}(f)}{\varepsilon_f^s f} - \frac{I_m s_e}{e^2} EMP_g - \frac{c^{'}(e)}{\varepsilon_e^s e}] - m_e \delta_e [\frac{I_m s_g}{g^2} EMP_g + \frac{c^{'}(g)}{\varepsilon_g^s g}] - \frac{s_g s_e I_m (m_g \delta_e + m_e \delta_g)}{ge\sigma} \\
&+ I_m \frac{m_g s_e g(\delta_g g s_e - \delta_e e s_g) + m_e \delta_e s_g^2 e^2 - m_e \delta_g s_e s_g g e}{g^2 e^2 \varepsilon_m^d}\}
\end{aligned}$$

Substituting $s_e = \frac{m_e e}{m}$ and $s_g = \frac{m_g g}{m}$ into the numerator in the last term of above expression yields

$$m_g s_e g(\delta_g g s_e - \delta_e e s_g) + m_e \delta_e s_g^2 e^2 - m_e \delta_g s_e s_g g e = s_g m \delta_g s_e^2 g - s_g m \delta_e e s_g s_e + s_e m \delta_e s_g^2 e - m \delta_g s_e^2 s_g g = 0$$

Therefore

$$\frac{dm}{dt} = \frac{1}{H}\{m_g \delta_g [\frac{p_f}{\varepsilon_f^d f} - \frac{c^{'}(f)}{\varepsilon_f^s f} - \frac{I_m s_e}{e^2} EMP_g - \frac{c^{'}(e)}{\varepsilon_e^s e}] - m_e \delta_e [\frac{I_m s_g}{g^2} EMP_g + \frac{c^{'}(g)}{\varepsilon_g^s g}] - \frac{s_g s_e I_m (m_g \delta_e + m_e \delta_g)}{ge\sigma}\} < 0 \tag{A9}$$

Appendix B: Comparative Static Analysis of a Biofuel Consumption Mandate

Totally differentiating (3.4) and (3.6) and combining $\bar{L} - f - e \geq 0$, we get

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

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

$$\frac{dg}{d\bar{e}} = \frac{1}{K} \begin{pmatrix} -\frac{\partial^2 U(m)}{\partial g \partial e} & 0 & 0 \\ 0 & U''_{ff} - c''(f) & -1 \\ -1 & 1 & 0 \end{pmatrix} = \frac{-1}{K} \frac{\partial^2 U(m)}{\partial g \partial e}$$

$$\frac{dg}{d\bar{e}} = \frac{-1}{K} . \frac{I_m s_e s_g}{g \bar{e}} \left(\frac{1}{\varepsilon_m^d} + \frac{1}{\sigma} \right) \qquad \text{(B1)}$$

Since $K < 0$, we have $\frac{dg}{d\bar{e}} < 0 \Leftrightarrow \left| \varepsilon_m^d \right| < \sigma$

$$\frac{df}{d\bar{e}} = \frac{1}{K} \begin{pmatrix} \frac{\partial^2 U(m)}{\partial g^2} - c''(g) & -\frac{\partial^2 U(m)}{\partial g \partial e} & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix} = \frac{-1}{K} \left(\frac{\partial^2 U(m)}{\partial g^2} - c''(g) \right) < 0 \qquad \text{(B2)}$$

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

(B3)

$$\frac{d(g+e)}{d\bar{e}}=\frac{dg}{d\bar{e}}+1=\frac{-1}{K}.\frac{I_m s_e s_g}{g\bar{e}}(\frac{1}{\varepsilon_m^d}+\frac{1}{\sigma})+1=\frac{1}{Kg\bar{e}}[Kg\bar{e}-I_m s_e s_g(\frac{1}{\varepsilon_m^d}+\frac{1}{\sigma})]$$

Where $Kg\bar{e}=[\frac{\partial^2 U(m)}{\partial g^2}-c^{''}(g)]g\bar{e}=[\frac{I_m s_g}{g^2}(\frac{s_g}{\varepsilon_m^d}-EMP_g)-\frac{p_g}{\varepsilon_g^s g}]g\bar{e}=\frac{I_m s_g \bar{e}}{g}(\frac{s_g}{\varepsilon_m^d}-EMP_g)-\frac{p_g \bar{e}}{\varepsilon_g^s}$

Therefore,

$$\frac{d(g+e)}{d\bar{e}}=\frac{1}{Kg\bar{e}}\{\frac{I_m s_g \bar{e}}{g}(\frac{s_g}{\varepsilon_m^d}-EMP_g)-\frac{p_g \bar{e}}{\varepsilon_g^s}-I_m s_e s_g(\frac{1}{\varepsilon_m^d}+\frac{1}{\sigma})\}$$

$$=\frac{1}{Kg\bar{e}}\{I_m s_g[\frac{(s_g\bar{e}-s_e g)}{g\varepsilon_m^d}-\frac{s_g s_e \bar{e}}{gEMP_e\sigma^2}-\frac{s_e}{\sigma}]-\frac{p_g \bar{e}}{\varepsilon_g^s}\}$$

(B4)

$$\frac{dGHG}{d\bar{e}}=\delta_g\frac{dg}{d\bar{e}}+\delta_e=\frac{-\delta_g}{K}.\frac{I_m s_e s_g}{g\bar{e}}(\frac{1}{\varepsilon_m^d}+\frac{1}{\sigma})+\delta_e$$

$$=\frac{1}{Kg\bar{e}}\{-\delta_g I_m s_e s_g(\frac{1}{\varepsilon_m^d}+\frac{1}{\sigma})+\delta_e[\frac{I_m s_g \bar{e}}{g}(\frac{s_g}{\varepsilon_m^d}-EMP_g)-\frac{p_g \bar{e}}{\varepsilon_g^s}]\}$$

$$=\frac{1}{Kg\bar{e}}\{\frac{-\delta_g I_m s_e s_g g+\delta_e I_m s_g^2 \bar{e}}{g\varepsilon_m^d}-\frac{\delta_e I_m s_g^2 s_e \bar{e}}{gEMP_e\sigma^2}-\frac{\delta_g I_m s_e s_g}{\sigma}-\frac{\delta_e p_g \bar{e}}{\varepsilon_g^s}\}$$

$$=\frac{1}{Kg\bar{e}}\{I_m s_g[\frac{\delta_e s_g \bar{e}-\delta_g s_e g}{g\varepsilon_m^d}-\frac{\delta_e s_g s_e \bar{e}}{gEMP_e\sigma^2}-\frac{\delta_g s_e}{\sigma}]-\frac{\delta_e p_g \bar{e}}{\varepsilon_g^s}$$

It can be re-written as

$$\frac{dGHG}{d\bar{e}}=\frac{1}{Kg\bar{e}}\{I_m s_g[\frac{\bar{e}}{\varepsilon_m^d m\delta_g m_e}(\frac{\delta_e p_g}{\delta_g(c^{'}(e)+\lambda)}-1)-\frac{\delta_e s_g s_e \bar{e}}{gEMP_e\sigma^2}-\frac{\delta_g s_e}{\sigma}]-\frac{\delta_e p_g \bar{e}}{\varepsilon_g^s} \qquad \text{(B5)}$$

$$
\begin{aligned}
\frac{dm}{d\bar{e}} &= m_g \frac{dg}{d\bar{e}} + m_e = \frac{-m_g}{K} . \frac{I_m s_e s_g}{g\bar{e}} \left(\frac{1}{\varepsilon_m^d} + \frac{1}{\sigma}\right) + m_e \\
&= \frac{1}{Kg\bar{e}} \{ m_e [\frac{I_m s_g \bar{e}}{g} \left(\frac{s_g}{\varepsilon_m^d} - EMP_g\right) - \frac{p_g \bar{e}}{\varepsilon_g^s}] - m_g I_m s_e s_g \left(\frac{1}{\varepsilon_m^d} + \frac{1}{\sigma}\right) \} \\
&= \frac{1}{Kg\bar{e}} \{ \frac{m_e I_m s_g^2 \bar{e} - m_g I_m s_e s_g g}{g\varepsilon_m^d} - \frac{m_e I_m s_g^2 \bar{e} s_e}{g\sigma^2 EMP_e} - \frac{m_g I_m s_e s_g}{\sigma} - \frac{m_e p_g \bar{e}}{\varepsilon_g^s} \} \qquad \text{(B6)} \\
&= \frac{-s_e m}{Kg\bar{e}} \{ \frac{I_m s_g^2 s_e}{g\sigma^2 EMP_e} + \frac{I_m s_g^2}{g\sigma} + \frac{p_g}{\varepsilon_g^s} \}
\end{aligned}
$$

Appendix C: Comparative Static Analysis of a Biofuel Consumption Mandate when Average Cost >Marginal Cost

This appendix analyzes impacts of the consumption mandate when blenders use average cost to price fuels. In this case VMT will be determined by average cost of fuels, and it yields the following equation:

$$P(m) = \frac{p_g(g)g + p(\bar{e})\bar{e}}{m} \tag{C1}$$

Where $p(\bar{e}) = c^{'}(\bar{e}) + \lambda$, is the sum of ethanol processing cost plus land rent. Totally differentiating (C1) yields:

$$\frac{dg}{d\bar{e}} = \frac{p(\bar{e})(1+\frac{1}{\varepsilon_e^s}) - P(m)m_e(1+\frac{1}{\varepsilon_m^d})}{-p_g(1+\frac{1}{\varepsilon_g^s}) + P(m)m_g(1+\frac{1}{\varepsilon_m^d})} < 0 \text{ if } \left|\varepsilon_m^d\right| \le 1 \tag{C2}$$

where ε_e^s is the elasticity of ethanol supply. As explained in the text this expression must be negative and thus $\left|\varepsilon_m^d\right| \le 1$.

As the consumption mandate increases, land allocated for food consumption would decrease, which in turn increases land rent. These two effects are shown in equation (C3):

$$\frac{df}{d\bar{e}} = \frac{d(\bar{L}-\bar{e})}{d\bar{e}} = -1 < 0, \text{ and } \frac{d\lambda}{d\bar{e}} > 0 \tag{C3}$$

$$\frac{d(g+e)}{d\bar{e}} = \frac{dg}{d\bar{e}} + 1 = \frac{p(\bar{e})(1+\frac{1}{\varepsilon_e^s}) - p_g(1+\frac{1}{\varepsilon_g^s}) + P(m)(m_g - m_e)(1+\frac{1}{\varepsilon_m^d})}{-p_g(1+\frac{1}{\varepsilon_g^s}) + P(m)m_g(1+\frac{1}{\varepsilon_m^d})} \tag{C4}$$

$$\frac{dGHG}{d\bar{e}} = \delta_g \frac{dg}{d\bar{e}} + \delta_e = \frac{\delta_g p(\bar{e})(1+\frac{1}{\varepsilon_e^s}) - \delta_e p_g (1+\frac{1}{\varepsilon_g^s}) + P(m)(\delta_e m_g - \delta_g m_e)(1+\frac{1}{\varepsilon_m^d})}{-p_g (1+\frac{1}{\varepsilon_g^s}) + P(m) m_g (1+\frac{1}{\varepsilon_m^d})} \tag{C5}$$

$$\frac{dm}{d\bar{e}} = m_g \frac{dg}{d\bar{e}} + m_e = \frac{m_g p(\bar{e})(1+\frac{1}{\varepsilon_e^s}) - m_e p_g (1+\frac{1}{\varepsilon_g^s})}{-p_g (1+\frac{1}{\varepsilon_g^s}) + P(m) m_g (1+\frac{1}{\varepsilon_m^d})} \tag{C6}$$

It can be seen that the impact of the mandate on total energy consumption and GHG emissions and VMT consumption in (C4), (C5) and (C6) is negative if elasticity of demand for miles is less than 1 and elasticity of gasoline supply is large.

The effect of an ethanol subsidy on total energy consumption and GHG emissions and VMT is shown in equations (C7), (C8) and (C9). Since $\frac{dg}{d\bar{e}}$ <0, all expressions below are positive. Thus a subsidy unambiguously increases energy consumption and GHG emissions and VMT relative to a mandate alone.

$$\frac{d(g+e)}{ds} = \frac{dg}{ds} = \frac{dg}{d\bar{e}} . \frac{d(p(\bar{e})-s)}{ds} / \frac{d(p(\bar{e})-s)}{d\bar{e}} = -\frac{\varepsilon_e^s \bar{e}}{p(\bar{e})} . \frac{dg}{d\bar{e}} \tag{C7}$$

$$\frac{dGHG}{ds} = \delta_g \frac{dg}{ds} = \frac{-\delta_g \varepsilon_e^s \bar{e}}{p(\bar{e})} . \frac{dg}{d\bar{e}} \tag{C8}$$

$$\frac{dm}{ds} = -\frac{m_g \varepsilon_e^s \bar{e}}{p(\bar{e})} . \frac{dg}{d\bar{e}} \tag{C9}$$

Appendix D: GMS Code for BEPAM

Version as of May 1, 2010

```
VARIABLE   SURPLUS                      Objective function value
POSITIVE VARIABLES
*Crop sector variables
   CONSUMP(T,sdtype,PRO)                Total amount of consumption
   COST(T,R)                            Total cost of all crops by region
   AGPROCONVERT(T,PRIMARY)              Conversion of primary commodities
   SELL(T,R,PRO)                        Commodity sales  (million bushels)
   CORN_TO_ETH(T,R)                     Use of corn for ethanol production
   PRO_TO_FEED(T,PRO,HERD)              Commodity used for feed
   BMASS(T,R)                           Amount of biomass production
   WEIGH(T,sdtype,PRO,NOGRID)           Weight variables for commodity consumption
   RESIDUE_TO_ETH(T,R,RESIDUE)          Use of crop residues for ethanol production
   RESIDUEQUAN(T,AGE)                   Amount of residues in each year

*land variables
   PASTURELAND(T,R,landtype)            Cropland pasture
   PLANT(T,R,ROT,TIL,IR)                Land planted by practices
   DSBACRE(T,R,IR)                      Double soybeans acreage
   PERACRE(T,R,PC,Age,landtype)         Acreage of perennials by age group
   TERMINAL(R,PC,Age,landtype)          Terminal acreages of perennials
   ACRES(T,R,CC,IR)                     Total acreage of row crops and alfalfa
   PER_NEW(T,R,PC,landtype)             Land planted for perennial crop PC
   LAMBDA(T,R,YR)                       Weight variables for historical crop mixes
   HYLAMBDA(T,R,N)                      Weight variables for hypothetical crop mixes
   IRRI_LAMBDA(T,R,YR,IR)               Weight variables for irrigated crop mixes
   RESIDUEACRE(T,R,ROT,TIL,IR)          Acres of crop residue producing residues

*Livestock sector variables
   CATTLEHEAD(T,R)                      Number of cattles
   CATTLELAMBA(T,YR)                    Weight variables for historical cattle
   TOTHERD(T,HERD)                      Total US livestock numbers
   LAMBAHERD(T,YR)                      Weight variables for historical livestock
   FEEDWEIGH(T,YR)                      Weight variables for historical feed
   TOTNUTRI(T,HERD,NUTRITION)           Total nutrition requirement for livestock
   MEAL_DAIRY(T)                        Cattle raised regularly
   SILAGE_DAIRY(T)                      Cattle raised by corn silage

*fuel sector varialbe
   MILECONSUMP(T)                       Miles consumption
   QCorn_Eth(T)                         Corn Ethanol Production
   QCel_Eth(T)                          Cellulosic Ethanol Production
   FUELSUPPLY(T,FUEL)                   Transportation fuels
```

```
   MILE_DEMANDWEIGH(T,nogrid)            Weigh for miles demand
   GAS_SUPWEIGH(T,gassource,point)
   MILE_SUPWEIGH(T,nogrid)               Weigh for miles supply
   GHGS(T)                               GHG emissions balance;

EQUATIONS
*objective function
   WELOBJECTIVE                          Welfare calculation
   RESIDLINK(T,AGE)                      Accounting crop residues in each year
*fuel market
   MILEDEMACCOUNT(T)                     Mileage demand accounting equation
   MILEDEMCONVEX(T)                      Mileage demand convex constraint
   MILEPROD(T)                           Mileage production function
   ETHSUPPLYEQ(T)                        Ethanol requirement for mile production
   GASSUPPLYEQ(T)                        Gasoline requirement for mile production
   ETHSUPPLY(T)                          Ethanol supply function
   GASSUPPLY(T)                          Gasoline supply equation
   GASWeigh(T,gassource)                 Gasoline supply convex

*agricultural markets
   PROACCOUNT(T,sdtype,PRO)              Accounting equation
   CONVEXWEIGH(T,sdtype,PRO)             Convex constraints of grids
   MATBAL(T,R,PRO)                       Domestic ag production balance
   PRICOMBAL(T,PRIMARY)                  Primary commodity balance
   SECCOMBAL(T,SECONDARY)                Secondary commodity balance
*livestock
   CATTLEGRAZE(T,R)                      Cattle grazing balance
   NUTRIDEM(T,HERD,NUTRITION)            Nutrition balance for each livestock
   ENERGYSOURCE(T,HERD)                  Grain energy balance
   OtherSource(T,FeedGrass)              Other nutrition balance
   PROTEINSOURCE(T,HERD)                 Protein balance
   HISTORICALFEED(T,FEEDHIST)            Historical mixes for feed consumption
   FEEDCONVEX(T)                         Convex for feed
   DDGLIMIT(T,HERD)                      DDG limits

   DAIRYCATTLEBAL(T)                     Dairy balance equation
   HERDHIST(T,HERD)                      Historical mixes for livestock
   HERDHISTCONVEX(T)                     Convex for livestock
   CATTLEHIST(T,R)                       Historical mixes for cattle
   CATTLEHISTCONVEX(T)                   Convex for cattle
   TLIVEPRODBAL(T,LIVESTOCK)             Livestock commodity balance
   TCATTLEBAL(T)                         Cattle balance equation

*LAND CONSTRAINT
   ROWACREAGE(T,R,CF,IR)                 Acreage accounting relating ACRES to PLANT
   DSOY(T,R,IR)                          Limit for soybean acreage as a second crop
```

```
    PERENNIAL(T,R,CC,Age,landtype)          Perennial crop acreages
    LINK(T,R,PC,Age,landtype)               Accounting terminal acres for perennials
    PERACREAGE(T,R,PC)                      Accounting equation for perennials
    LAND(T,R)                               Land availability constraints
    TOTLANDAV(T,R)                          Total land avail constraints incluidng all
    GRASSLIMIT(T,R)                         Constraints for land allocated to perennials
    MARGINALLANDBAL(T,R,landtype)           Marginal land balances
    ACREHIST(T,R,CC)                        Historical mixes for row crops
    IRRIACREHIST(T,R,HC,IR)                 Historical mixes for irrigated row crops
    LANDCONVEX(T,R)                         Convex for acres under row crops
    IRRILANDCONVEX(T,R,IR)                  Convex for acres under irrigated row crops
    TCOST(T,R)                              Total cost accounting eqn by region by time
    RESIDPROD(T,R,RESIDUE)                  Relates stover production to stover acres
    RESIDACRE(T,R,ROT,TIL,IR)               Equation for total acres producing stover
    BIOMASS(T,R)                            Biomass production equation
    CORN_ETHAN(T)                           Corn ethanol production balance
    CEL_ETHAN(T)                            Cellulosic ethanol production balance
    CORNETH_MANDATE(T)                      Corn ethanol mandates
    CELLETH_MANDATE(T)                      Cellulosic ethanol mandates
    ETH_MANDATE(T)                          Total biofuel mandates
    TOTEMISSIONS(T)                         GHG emissions balance;

WELOBJECTIVE.. SURPLUS =E= Sum(T$(ord(T)le 10),(1/(1+disc))**(Ord(T)-1)*
*commodity surplus
 (  Sum((sdtype,PRO,NOGRID)$(ord(sdtype)le 2
      and commoddem(sdtype,PRO,'elasticity') and supdem_promap(PRO,sdtype)),
           GridSurplus(sdtype,PRO,NOGRID)*WEIGH(T,sdtype,PRO,NOGRID))

 + Sum((sdtype,PRO)$(ord(sdtype)le 2 and commoddem(sdtype,PRO,'elasticity') eq 0
      and supdem_promap(PRO,sdtype)),
          commoA(sdtype,PRO)*CONSUMP(T,sdtype,PRO))

 - Sum((sdtype,PRO,NOGRID)$(ord(sdtype) eq 3
      and commoddem(sdtype,PRO,'elasticity') and supdem_promap(PRO,sdtype)),
          GridSurplus(sdtype,PRO,NOGRID)*WEIGH(T,sdtype,PRO,NOGRID))

 - Sum((sdtype,PRO)$(ord(sdtype)eq 3 and commoddem(sdtype,PRO,'elasticity') eq 0
      and supdem_promap(PRO,sdtype)),
           commoA(sdtype,PRO)*CONSUMP(T,SDTYPE,PRO))

*surplus from miles consumption
  + Sum(NOGRID, MileSurplus(nogrid)*MILE_DEMANDWEIGH(T,nogrid))

*agricultural production costs
  -  Sum(R, COST(T,R))
```

```
*livestock production costs
  - sum(ANIMAL,
   LiveProcessCost(ANIMAL)* sum(HERD,
TOTHERD(T,HERD)*AnimalShare(Animal,Herd)))

*primary commodity processing costs
  - sum(PRIMARY, AgProcessCost(PRIMARY)* AGPROCONVERT(T,PRIMARY))

*ethanol processing costs, fuel tax and subsidiy
  - (cornethprocess +CornEthRet +Markup +FuelTax -CornEthSub
     + EthTranport('CORN') )*QCorn_Eth(T)
  - (cellethprocess +CellEthRet +Markup +FuelTax -CELL_COPRO -CellEthSub
     + EthTranport('CEL'))*QCel_Eth(T)

*Gasoline cost
  - Sum((gassource,point),
          GasCostGrid(gassource,point)*GAS_SUPWEIGH(T,gassource,point))

*Biomass subsidy
  + Sum((R,EC,Age,landtype)$(FLAG(R,EC,'total') and ord(landtype) le 3),
      (Estab_sub(T) *1/2.471*PERCOST_EST(R,EC,AGE)
           + Estab_land* landrent(R,landtype)$PERCOST_EST(R,EC,AGE))
                                  *PERACRE(T,R,EC,Age,landtype))

  + Harv_Sub(T) *Sum((R,Age,landtype)$(Ord(age) ge 3 and ord(age) le 4
                  and FLAG(R,'MI','total') and ord(landtype) le 3),
                    BmassYield(R,'MI',age)*PERACRE(T,R,'MI',Age,landtype))

  + Harv_Sub(T) *Sum((R,Age,landtype)$(Ord(age) ge 2 and ord(age) le 3
                  and FLAG(R,'SG','total') and ord(landtype) le 3),
                    BmassYield(R,'SG',age)*PERACRE(T,R,'SG',Age,landtype))

  + sum(AGE$(ord(AGE) le 2), Residue_Sub(T)*RESIDUEQUAN(T,AGE))

  - CarbonTax* GHGS(T)

*land conversion cost from marginal to cropland
  - sum((R,EC,landtype)$(Flag(R,EC,'Total')
          and ord(landtype) ge 2 and ord(landtype) le 3),
                    Landcost(R)*PERACRE(T,R,EC,'1',landtype))
))

  + ((1/(1+disc))**(cardinal))*
      ( sum(R, sum((EC,AGE)$(ord(age) Le life(EC)),
          (termval(R,EC,age)-termrowval(R))*TERMINAL(R,EC,Age,'regular')))
      + sum(R, sum((EC,AGE,landtype)$(ord(age) LE life(EC)
```

```
              and ord(landtype) ge 2 and ord(landtype) le 3),
            (termval(R,EC,age)-Landcost(R))*TERMINAL(R,EC,Age,landtype)))
        );

RESIDLINK(T,AGE)$(ord(T)le 10)..
  RESIDUEQUAN(T,AGE)=e= RESIDUEQUAN(T-1,AGE-1)$(ord(AGE) gt 1) +
    (sum((R,residue), RESIDUE_TO_ETH(T,R,RESIDUE))
        - sum((R,residue), RESIDUE_TO_ETH(T-1,R,RESIDUE)))$(ord(AGE) eq 1);

*demand and supply balances of mils and fuels
MILEDemACCOUNT(T)$(ord(T)le 10)..
   MILECONSUMP(T) =e= sum(NOGRID,
MILE_DEMANDWEIGH(T,nogrid)*MileGrid(nogrid));

MILEDemCONVEX(T)$(ord(T)le 10)..
   sum(NOGRID, MILE_DEMANDWEIGH(T,nogrid))=e=1;

MILEPROD(T)$(ord(T)le 10)..
   MILECONSUMP(T)=E= sum(nogrid, MileSupply(nogrid)*MILE_SUPWEIGH(T,nogrid));

*fuels demand and supply balance
ETHSUPPLYEQ(T)$(ord(T)le 10)..
   FUELSUPPLY(T,'ethanol') =e=
                  sum(nogrid,MILE_SUPWEIGH(T,nogrid)*EthGrid(nogrid));

GASSUPPLYEQ(T)$(ord(T)le 10)..
   FUELSUPPLY(T,'gas') =e=
                  sum(nogrid, MILE_SUPWEIGH(T,nogrid)*GasGrid(nogrid));

ETHSUPPLY(T)$(ord(T)le 10)..
   FUELSUPPLY(T,'ethanol')=e= QCorn_Eth(T)+ QCel_Eth(T);

GASSUPPLY(T)$(ord(T)le 10)..
   FUELSUPPLY(T,'gas') =e= sum((gassource,point),
              GAS_SUPWEIGH(T,gassource,point)*Gaspoint(gassource,point));

GASWeigh(T,gassource)$(ord(T)le 10)..
    sum(point,GAS_SUPWEIGH(T,gassource,point)) =l= 1;

*commodity consumption and supply balance in crop sector
PROACCOUNT(T,sdtype,PRO)$(ord(T)le 10
       and commoddem(sdtype,PRO,'elasticity') and supdem_promap(PRO,sdtype))..
    CONSUMP(T,sdtype,PRO)=e=
          sum(NOGRID, WEIGH(T,sdtype,PRO,NOGRID)* Grid(sdtype,pro,nogrid));

CONVEXWEIGH(T,sdtype,PRO)$(ord(T)le 10
```

```
      and commoddem(sdtype,PRO,'elasticity') and supdem_promap(PRO,sdtype))..
          Sum(NOGRID, WEIGH(T,sdtype,PRO,NOGRID))=e=1;

*Regional primary commodity balance
MATBAL(T,R,PRIMARY)$(SUM(IRR,ProdFlag(R,IRR,PRIMARY)) and ord(T)le 10)..

  SELL(T,R,PRIMARY) + CORN_TO_ETH(T,R)$(Ord(PRIMARY) eq 1)
  =E= sum(IRR$ProdFlag(R,IRR,PRIMARY),
      Sum((ROT,TIL)$(Rot_Map(R,ROT) and ROT_TILmap(ROT,TIL)),
                   Yield(R,ROT,PRIMARY,TIL,IRR)*PLANT(T,R,ROT,TIL,IRR))
     + CropYield(R,IRR,'DSB')*SurvRate(R,'dsb',IRR)
              *DSBACRE(T,R,IRR)$(PROMap('dsb',PRIMARY)*Flag(R,'dsb',IRR)));

*******National PRIMARY agricultural commodity balance
PRICOMBAL(T,PRIMARY)$(ord(T)le 10)..

CONSUMP(T,'US_dom_demand',PRIMARY)$supdem_promap(PRIMARY,'US_dom_demand')
=E=
    Sum(R$SUM(IRR,ProdFlag(R,IRR,PRIMARY)), SELL(T,R,PRIMARY))
  +  CONSUMP(T,'US_imports',PRIMARY)$supdem_promap(PRIMARY,'US_imports')
  -  CONSUMP(T,'US_exports',PRIMARY)$supdem_promap(PRIMARY,'US_exports')
  -  AGPROCONVERT(T,PRIMARY)$AgProcessCost(primary)
  -  sum(HERD, PRO_TO_FEED(T,PRIMARY,HERD)$Feed(PRIMARY));


SECCOMBAL(T,SECONDARY)$(ord(T)le 10)..

CONSUMP(T,'US_dom_demand',SECONDARY)$supdem_promap(SECONDARY,'US_dom_d
emand')
  =E=
     SUM(PRIMARY$AgProcessCost(primary),
           Agconvertecoef(PRIMARY,SECONDARY)*AGPROCONVERT(T,PRIMARY))
   +
CONSUMP(T,'US_imports',SECONDARY)$supdem_promap(SECONDARY,'US_imports')
   - CONSUMP(T,'US_exports',SECONDARY)$supdem_promap(SECONDARY,'US_exports')
   - sum(HERD, PRO_TO_FEED(T,SECONDARY,HERD)$Feed(SECONDARY))
   + (DDGS/shortton)* sum(R$(sum(IRR,Flag(R,'co',IRR))),
                          CORN_TO_ETH(T,R))$(ord(SECONDARY) eq 1);

****************************Livestock Sector**********************************
CATTLEGRAZE(T,R)$(ord(T)le 10 and Flag_cattle(R))..
  CATTLEHEAD(T,R)* AnimalShare('CowCalf','Cattle') =L=
  sum(Grazetype$(ord(Grazetype) ge 2 and ord(Grazetype) le 3
        and AUM(R,Grazetype)), countypasture(R,Grazetype)/Aum(R,Grazetype))
+ sum(Grazetype$(ord(Grazetype) eq 1 and AUM(R,Grazetype)),
                   PASTURELAND(T,R,'croppasture')/Aum(R,Grazetype))
```

```
**crop residues for grazing
+ sum(Grazetype$(ord(Grazetype) ge 4 and AUM(R,Grazetype)),
  sum((IRR,CC)$(Graze_Crop(CC,Grazetype) and Flag(R,CC,IRR)),
                                   ACRES(T,R,CC,IRR))/Aum(R,Grazetype));

*livestock sector commodity balance
NUTRIDEM(T,HERD,NUTRITION)$(ord(T) le 10 and
HERD_TO_NUTRITION(HERD,NUTRITION))..
  TOTNUTRI(T,HERD,NUTRITION) =e=
  sum(ANIMAL, TOTHERD(T,HERD)* AnimalShare(Animal,Herd)
                       * animalnutrireq(animal,nutrition))$(ord(Herd) ne 2)
+ MEAL_DAIRY(T)* animalnutrireq('DAIRY',nutrition)$(ord(Herd) eq 2);

ENERGYSOURCE(T,HERD)$(ord(T) le 10)..
  sum(GrainNutri$HERD_TO_NUTRITION(HERD,GrainNutri),
                              TOTNUTRI(T,HERD,GrainNutri))*cwt =E=
  sum(FeedEnergy, PRO_TO_FEED(T,FeedEnergy,HERD)*FeedWeighConvert(FeedEnergy));

OtherSource(T,FeedGrass)$(ord(T) le 10)..
  DairyAlter(FeedGrass)* SILAGE_DAIRY(T) =e= PRO_TO_FEED(T,FeedGrass,'Dairy');

PROTEINSOURCE(T,HERD)$(ord(T) le 10)..
  sum(ProNutri$HERD_TO_NUTRITION(HERD,ProNutri),
                       TOTNUTRI(T,HERD,ProNutri))*cwt/shortton
 + Dairy_Soymeal* MEAL_DAIRY(T)$(ord(Herd) eq 2) =E=
  PRO_TO_FEED(T,'SoybeanMeal',HERD) + PRO_TO_FEED(T,'DDG',HERD)*
DDGMEALRatio;

HISTORICALFEED(T,FeedHist)$(ord(T) le 10)..
  sum(HERD, PRO_TO_FEED(T,FeedHist,HERD)) =E=
     sum(YR$(ord(YR) ge 9 and ord(YR) le 18),
                       HistFeed(YR,FeedHist) * FEEDWEIGH(T,YR));

FEEDCONVEX(T)$(ord(T) le 10)..
  sum(YR$(ord(YR) ge 9 and ord(YR) le 18), FEEDWEIGH(T,YR)) =L=1;

DDGLIMIT(T,HERD)$(ord(T) le 10)..
  PRO_TO_FEED(T,'DDG',HERD)*FeedWeighConvert('DDG')=L=
  sum(FEED,
PRO_TO_FEED(T,FEED,HERD)*FeedWeighConvert(FEED))*LiveDDGLim(HERD);

DAIRYCATTLEBAL(T)$(ord(T) le 10)..
  MEAL_DAIRY(T) + SILAGE_DAIRY(T) =e= TOTHERD(T,'DAIRY');

HERDHIST(T,HERD)$(ord(T) le 10 and ord(herd) ne 1)..
  TOTHERD(T,HERD) =e=
```

```
sum(YR$(ord(YR) ge 10 and ord(YR) le 18), Histnoherd(yr,Herd)* LAMBAHERD(T,YR));

HERDHISTCONVEX(T)$(ord(T) le 10)..
  sum(YR$(ord(YR) ge 10 and ord(YR) le 18), LAMBAHERD(T,YR))=l=1;

CattleHist(T,R)$(ord(T) le 10 and Flag_cattle(R))..
       CATTLEHEAD(T,R)=e= sum(YR$(ord(YR) le 18),
                    cattlenumber(R,yr,'Nocattle')* CATTLELAMBA(T,YR));

CATTLEHISTCONVEX(T)$(ord(T) le 10)..
  sum(YR$(ord(YR) le 18), CATTLELAMBA(T,YR))=l=1;

*livestock balance
TLIVEPRODBAL(T,LIVESTOCK)$(ord(T) le 10)..
CONSUMP(T,'US_dom_demand',livestock)$supdem_promap(livestock,'US_dom_demand')=E=
  CONSUMP(T,'US_imports',livestock)$supdem_promap(livestock,'US_imports')
 - CONSUMP(T,'US_exports',livestock)$supdem_promap(livestock,'US_exports')
 + sum(HERD, TOTHERD(T,HERD)* Herd_Pro(LIVESTOCK,HERD));

TCATTLEBAL(T)$(ord(T) le 10)..
      TOTHERD(T,'Cattle')=e=  sum(R$Flag_cattle(R), CATTLEHEAD(T,R));

****************crop sector**************************************************
ROWACREAGE(T,R,CF,IRR)$(FLAG(R,CF,IRR) and ord(T)le 10)..
ACRES(T,R,CF,IRR) =e=  Sum(ROT$(RotMap(ROT,CF) and Rot_Map(R,ROT)),
          SUM(TIL$ROT_TILmap(ROT,TIL),Share(ROT,CF)*PLANT(T,R,ROT,TIL,IRR)))
             +  DSBACRE(T,R,IRR)$(Ord(CF) eq 2 and Flag(R,'dsb',IRR));

DSOY(T,R,IRR)$(Flag(R,'dsb',IRR) ne 0 and ord(T)le 10)..
          DSBACRE(T,R,IRR)=L= sum(PDC$Flag(R,PDC,IRR),ACRES(T,R,PDC,IRR));

PERENNIAL(T,R,EC,Age,landtype)$(Ord(Age) le Life(EC)
        and ord(T)le 10 and FLAG(R,EC,'Total') and ord(landtype) le 3)..
PERACRE(T,R,EC,Age,landtype)  =e=
    InitPlant(R,EC,Age,landtype)$(Ord(T) eq 1 and Ord(Age) gt 1)
  + PER_NEW(T,R,EC,landtype)$(Ord(age) eq 1)
  + PERACRE(T-1,R,EC,Age-1,landtype)$(Ord(age) ge 2);

LINK(T,R,EC,Age,landtype)$(Ord(Age) le Life(EC)
        and ord(T) eq 10 and FLAG(R,EC,'Total') and ord(landtype) le 3)..
  PERACRE(T,R,EC,Age,landtype)  =e=  TERMINAL(R,EC,Age,landtype);

PERACREAGE(T,R,EC)$(Flag(R,EC,'Total') and ord(T)le 10)..
    ACRES(T,R,EC,'Total')=E=
          Sum((Age,landtype)$(Ord(Age) le Life(EC) and ord(landtype) le 3),
                    PERACRE(T,R,EC,Age,landtype));
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LAND(T,R)$(ord(T)le 10)..
     Sum((ROT,TIL,IRR)$(Rot_Map(R,ROT) and ROT_TILmap(ROT,TIL)),
     PLANT(T,R,ROT,TIL,IRR))
   +  Sum((Age,EC)$(Ord(Age) le Life(EC)), PERACRE(T,R,EC,Age,'regular'))
     =L=  landav3(R);

MARGINALLANDBAL(T,R,landtype)$(ord(T)le 10 and ord(landtype) ge 2
                   and ord(landtype) le 3)..
   PASTURELAND(T,R,landtype)$(ord(landtype) eq 3)
 +  Sum((Age,EC)$(Ord(Age) le Life(EC)), PERACRE(T,R,EC,Age,landtype))
   =l= marginalland(R,landtype,'value');

TOTLANDAV(T,R)$(ord(T)le 10)..
   landav3(R)+ PASTURELAND(T,R,'croppasture') +
   Sum((Age,EC,landtype)$(Ord(Age) le Life(EC) and ord(landtype) ge 2
       and ord(landtype) le 3), PERACRE(T,R,EC,Age,landtype))  =l= totland(R);

GRASSLIMIT(T,R)$(ord(T)le 10)..
  Sum((Age,EC,landtype)$(Ord(Age) le Life(EC) and ord(landtype) le 3),
        PERACRE(T,R,EC,Age,landtype)) =L=  peracrelim *totland(R) ;

ACREHIST(T,R,HC)$(sum(IRR,Flag(R,HC,IRR)) and ord(T)le 10)..
sum(IRR$(Flag(R,HC,IRR)), ACRES(T,R,HC,IRR)) =e=
  Sum(YR$(ord(YR)ge 6 and ord(YR) le 18),
     sum(IRR,acresdata(R,YR,HC,IRR))*LAMBDA(T,R,YR))
 + Sum(N, hyacre(N,R,HC)*HYLAMBDA(T,R,N));

LANDCONVEX(T,R)$(ord(T)le 10)..
  Sum(Yr$(Ord(Yr) le hy and ord(YR)ge 6), LAMBDA(T,R,YR))
 + Sum(N, HYLAMBDA(T,R,N))=L= 1;

IRRIACREHIST(T,R,HC,IRR)$(Flag(R,HC,IRR) and ord(T)le 10 and ord(IRR) eq 1)..
ACRES(T,R,HC,IRR) =e=  Sum(YR$(ord(YR)ge 6 and ord(YR) le 18),
                      acresdata(R,YR,HC,IRR)*IRRI_LAMBDA(T,R,YR,IRR));

IRRILANDCONVEX(T,R,IRR)$(ord(T)le 10 and ord(IRR) eq 1)..
  Sum(Yr$(Ord(Yr) le hy and ord(YR)ge 6), IRRI_LAMBDA(T,R,YR,IRR))=L= 1;

*total production cost
TCOST(T,R)$(ord(T)le 10)..
  COST(T,R)=E= (1/2.471)*(
  Sum((ROT,TIL,IRR)$(Rot_Map(R,ROT)*ROT_TILmap(ROT,TIL)),
                      RotTilCost(R,Rot,Til,IRR)*PLANT(T,R,ROT,TIL,IRR))
 + Sum((EC,Age,landtype)$(Flag(R,EC,'Total') and ord(Age) le life(EC)
      and ord(landtype) le 3), PerCost(R,EC,Age)* PERACRE(T,R,EC,AGE,landtype))
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 + Sum((ROT,TIL,IRR)$(sum(RF, FLAG(R,RF,IRR)) and Rot_Map(R,ROT)
  and ROT_TILmap(ROT,TIL)), resiadj(R,Rot,TIL,IRR)*RESIDUEACRE(T,R,ROT,TIL,IRR))
 + Sum(IRR, DsbCost(R,IRR)*DSBACRE(T,R,IRR)$Flag(R,'dsb',IRR)) );
* all costs are $/ha 2.471 converts to $/acre 1 ha =2.471 acres

RESIDPROD(T,R,RESIDUE)$(ord(T)le 10)..
  RESIDUE_TO_ETH(T,R,RESIDUE)=e=
  sum((Rot,Til,IRR)$(ProdFlag(R,IRR,RESIDUE) and Rot_Map(R,ROT)
                 and ROT_TILmap(ROT,TIL) and resiadj(R,Rot,TIL,IRR)),
          Yield(R,ROT,residue,TIL,IRR)* RESIDUEACRE(T,R,ROT,TIL,IRR));

RESIDACRE(T,R,ROT,TIL,IRR)$(ord(T)le 10 and sum(RF,Flag(R,RF,IRR))
                   and sum(RF,RotMap(ROT,RF)) and Rot_Map(R,ROT))..
  RESIDUEACRE(T,R,ROT,TIL,IRR)=L= PLANT(T,R,ROT,TIL,IRR) ;

BIOMASS(T,R)$(ord(T)le 10)..
  BMASS(T,R) =e= sum(residue, RESIDUE_TO_ETH(T,R,RESIDUE)) +
    Sum((EC,Age,landtype)$(Ord(age) le life(EC) and Flag(R,EC,'Total')
   and ord(landtype) le 3), BmassYield(R,EC,age)*PERACRE(T,R,EC,Age,landtype));

CORN_ETHAN(T)$(ord(T)le 10)..
 Sum(R$(sum(IRR,Flag(R,'co',IRR))), CORN_ETH*CORN_TO_ETH(T,R)) =e=
QCorn_Eth(T);

CEL_ETHAN(T)$(ord(T)le 10)..  Sum(R, cel_eth*BMASS(T,R)) =e= QCel_Eth(T);

CORNETH_MANDATE(T)$(ord(T)le 10)..
   QCorn_Eth(T)  =l= ETH_TARGET(T,'CORN');

CELLETH_MANDATE(T)$(ord(T)le 10)..
  QCel_Eth(T) =g= ETH_TARGET(T,'CEL')- ETH_TARGET(T,'ADVANCED');

ETH_MANDATE(T)$(ord(T)le 10)..
  FUELSUPPLY(T,'ethanol') =g= sum(ETH$(ord(ETH) le 2), ETH_TARGET(T,ETH));

TOTEMISSIONS(T)$(ord(T)le 10)..

  GHGS(T) =e= 1/ton_kg*(Gasemission* FUELSUPPLY(T,'gas')
 + sum((environ,R,CF,TIL,IRR)$Flag(R,CF,IRR),
      itememission(environ)* RowEnviro(R,CF,TIL,IRR,environ)*(
    sum(Rot$(RotMap(ROT,CF) and ROT_TILmap(ROT,TIL) and Rot_Map(R,ROT)
             and ord(ROT) ne 1), Share(ROT,CF)*PLANT(T,R,ROT,TIL,IRR))))
 + sum((environ,R,TIL,IRR)$(ROT_TILmap('COSB',TIL) and Rot_Map(R,'COSB')),
        itememission(environ)* (RowEnviro(R,'COSB',TIL,IRR,environ)
        + RowEnviro(R,'SB',TIL,IRR,environ))* 0.5*PLANT(T,R,'COSB',TIL,IRR))
 + sum((environ,R,TIL,IRR)$Flag(R,'dsb',IRR),
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    itememission(environ)*RowEnviro(R,'SB',TIL,IRR,environ)*DSBACRE(T,R,IRR))
+ sum((environ,R,EC,AGE,landtype)$(ord(Age) le life(EC)
        and Flag(R,EC,'Total') and ord(landtype) le 3),
  itememission(environ)* PerEnviro(R,EC,environ)*PERACRE(T,R,EC,Age,landtype))
+ sum((environ,R,ROT,TIL,IRR)$(ROT_TILmap(ROT,TIL) and Rot_Map(R,ROT)),
          itememission(environ)* rEnviro(R,ROT,TIL,IRR,environ)
                                  * RESIDUEACRE(T,R,ROT,TIL,IRR))
+ (Ref_corneth-1.0)* QCorn_Eth(T) + (0.28-0.40)* QCel_Eth(T) );
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Endnotes:

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[1] http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_public_laws&docid=f:publ246.pdf

[2] Ethanol Imports and the Caribbean Basin Initiative. CRS Report RS21930. http://renergie.wordpress.com/2008/07/31/ethanol-imports-and-the-caribbean-basin-initiative/

[3] http://www.caribbeandailynews.com/?p=1569

[4] 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 changesSearchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu. 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." *Science* 319 (5867): 1238-1240..

[5] http://www.agmrc.org/renewable_energy/ethanol/the_relationship_of_ethanol_gasoline_and_oil_prices.cfm#

[6] 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.

[7] By solving cost minimization of miles production, the marginal cost (or price of miles *P(m)*) of miles is expressed as $P(m) = \frac{1}{\gamma}(a^{\sigma} p_g^{1-\sigma} + (1-a)^{\sigma} p_e^{1-\sigma})^{1/1-\sigma}$

[8] Specifically, we group the USDA Farm Production Regions (see Economic Research Service (ERS), 2009) into the following five major regions: West for Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington and Wyoming, Plains for Nebraska, North Dakota, Oklahoma, South Dakota, Texas and Kansas, Midwest for Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin, South for Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi and South Carolina, and Atlantic for Kentucky, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Tennessee, Virginia, and West Virginia.

[9] http://southwestfarmpress.com/energy/121107-switchgrass-challenges/
http://www.osti.gov/bridge/servlets/purl/771591-9J657S/webviewable/771591.pdf

[10] Delivered yields incorporate losses during harvesting, storing and transporting. Switchgrass yield is typically about one-third of that for miscanthus. Exceptions to this are some northern states and some southern states where switchgrass yields are relatively higher than those for miscanthus because minimum temperature are too low in the north and not low enough in the south for miscanthus growth. Perlaack et al. (2005) assume switchgrass yields of 18 DMT ha^{-1} in a high yield scenario and 12 DMT ha^{-1} otherwise.

[11] http://cost.jsc.nasa.gov/inflateGDP.html

[12] http://www.extension.org/pages/Miscanthus_for_Biofuel_Production

[13] Information on crop rotation for each state is obtained from ERS/USDA report "Production Practices for Major Crops in US Agriculture, 1990-1997"

[14] www.farmdoc.uiuc.edu

[15] http:/www.ers.usda.gov/Data/MajorLandUses

[16] An exception is the price of milk which is kept fixed at its observed 2006-2007 level.

[17] http://www.fapri.iastate.edu/outlook/2010/text/Outlook_2010.pdf

[18] We obtain historical data on vehicle miles travelled (VMT) from Federal Highway Administration website: http://www.fhwa.dot.gov/policyinformation/statistics/2008/vm202.cfm, and use average growth rate of VMT from 2000-2008.

[19] Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards. 2002. National Research Council.

[20] www.neo.ne.gov/statshtml/66.html

[21] Transportation cost of ethanol is estimated to be \$0.02 per liter in Lasco et al (2009). The difference in ethanol prices in Brazil and CBA countries can be attributed to additional processing cost in CBA countries because ethanol needs to be dehydrated before admitted to the U.S.

[22] 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.