DISSERTATION

# GLOBAL IMPACTS OF U.S. BIOENERGY PRODUCTION AND POLICY: A GENERAL EQUILIBRIUM PERSPECTIVE

Submitted by

Samuel Garner Evans

Department of Agricultural and Resource Economics

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2012

Doctoral Committee:

Advisor: Dana Hoag

Craig Bond
Stephen Davies
Keith Paustian

# ABSTRACT

## GLOBAL IMPACTS OF U.S. BIOENERGY PRODUCTION AND POLICY: A GENERAL EQUILIBRIUM PERSPECTIVE

The conversion of biomass to energy represents a promising pathway forward in efforts to reduce fossil fuel use in the transportation and electricity sectors. In addition to potential benefits, such as greenhouse gas reductions and increased energy security, bioenergy production also presents a unique set of challenges. These challenges include tradeoffs between food and fuel production, distortions in energy markets, and terrestrial emissions associated with changing land-use patterns. Each of these challenges arises from market-mediated responses to bioenergy production, and are therefore largely economic in nature.

This dissertation directly addresses these opportunities and challenges by evaluating the economic impacts of U.S. bioenergy production and policy, focusing on both existing and future biomass-to-energy pathways. The analysis approaches the issue from a global, economy-wide perspective, reflecting two important facts. First, that large-scale bioenergy production connects multiple sectors of the economy due to the use of agricultural land resources for biomass production, and competition with fossil fuels in energy markets. Second, markets for both agricultural and energy commodities are highly integrated globally, causing domestic policies to have international effects.

The reader can think of this work as being comprised of three parts. Part I provides context through an extensive review of the literature on the market-mediated effects of conventional biofuel production (Chapter 2) and develops a general equilibrium modelling

framework for assessing the extent to which these phenomenon present a challenge for future bioenergy pathways (Chapter 3). Part II (Chapter 4) explores the economic impacts of the lignocellulosic biofuel production targets set in the U.S. Renewable Fuel Standard on global agricultural and energy commodity markets. Part III (Chapter 5) extends the analysis to consider potential inefficiencies associated with policy-induced competition for biomass between the electricity and transportation fuel sectors.

# ACKNOWLEDGEMENTS

I would first like to thank my advisor, Dr. Dana Hoag. Your guidance, wisdom, perspective, and friendship has made all of this possible. Thank you to my committee members, Dr. Craig Bond, Dr. Keith Paustian, and Dr. Steve Davies, for all the hours that you invested over the years. Your insights have been invaluable. I also thank Dr. Ron Sands and Dr. Jayson Beckman at the Economic Research Service for their guidance and support as I wondered through the world of CGE modeling. Without them, the black box would have been a black hole.

I feel especially lucky for getting to know a great group of interdisciplinary researchers through the CSU MASB program. Each of you has contributed in a unique and important way throughout this journey. John and Paul, I thank you guys for making graduate school the best five years of my life. Barb, thank you for helping me navigate all obstacles, both large and small.

To all of my friends, thank you. I could never begin to articulate just how important each one of you has been in my life.

Most importantly, thanks to my family. Mom and Dad, I am forever indebted to you for the unconditional love and support that you have provided over the years. Rebecca, the greatest sister in the world. Period. Brent, you are and always have been my role model. I dedicate this work to my great-grandmother, Geneva Garner. An educator of the first-order and truly inspiring woman.

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# Chapter 1

# Organization of Dissertation

This dissertation is comprised of five chapters, including this introduction. Chapter 2 provides an extensive literature review on the economic impacts of biofuel production, focusing in particular on two adverse effects, distortions in non-bioenergy commodity markets and greenhouse gas emissions associate with biofuel-induced land-use change. Chapter 3 describes the analytical framework used for the research in this dissertation. This includes full documentation of the Future Agricultural Resources Model (FARM), a global computable general equilibrium (CGE) model used for agricultural and energy policy analysis. The methodology for expanding FARM to include a detailed bioenergy module is also described.

Chapter 4 presents the first set of results in this dissertation. The study incorporates several cellulosic biofuel pathways into the CGE modeling framework and explores impacts of an aggressive cellulosic bioenergy expansion on domestic and global agricultural commodity and land markets. A comprehensive and quantitative review of the economic literature on cellulosic feedstock and biofuel production is used to develop an advanced biofuel module in FARM. Cellulosic biofuel production is then integrated into the CGE modeling platform by altering the base year social accounting matrix to analyze the domestic and global economic effects of scaling up production. Simulations of the U.S. biofuel production mandate (the Renewable Fuel Standard) are conducted, which highlight important economic tradeoffs associated with advanced biofuel production. Emphasis is placed on economic variables such as prices, production levels, bilateral trade, and land-use, rather than environmental factors, such as greenhouse gas emissions.

Chapter 5 presents the second set of results. This study examines interactions in the feedstock sector under two different types of bioenergy policy instruments. With a carbon-tax, projected to divert cellulosic biomass primarily towards bioelectricity production, and a biofuel production mandate, designed to divert cellulosic biomass towards renewable transportation fuel, I estimate the efficiency implications of jointly implementing both renewable energy policies. A conceptual model highlighting the potential effects of these dueling policies in order to develop a hypothesis regarding welfare effects. This hypothesis is then tested using FARM.

Chapters 4 and 5 are written to be directly submitted to peer-reviewed journals. Therefore, each of these chapters stands along, which leads to some redundancy with Chapters 2 and 3. Each contains an abbreviated literature review relevant to the topic of interest, as well as a methodology section describing any important extensions to the methodological approach outlined in Chapter 3. The dissertation as a whole is be an integrated assessment of the economic and environmental impacts of U.S. bioenergy production, with a strong emphasis on potential future production pathways.

# Chapter 2

## Background and Review

This chapter is organized as follows. Section 2.1 provides an overview of the U.S. biofuel industry, as it has emerged since 2000 (section 2.1.1), and federal policy instruments put in place to provide incentives for the production and consumption of biofuels as part of the domestic transportation fuel portfolio (section 2.1.2). Section 2.2 reviews the literature on the economic impacts of conventional biofuel production with regards to domestic and global commodity markets, focusing on agricultural commodities (section 2.2.1), livestock markets (section 2.2.2), and transportation fuel markets (section 2.2.3). This section also reviews the literature on the welfare impacts of U.S. biofuel policies (section 2.2.4). Section 2.3 analyzes the impacts of biofuel production on land-use change and subsequent terrestrial greenhouse gas emissions. In addition to reporting results from a variety of economic models, this section also outlines important methodological issues on approaches to parameterizing, measuring, and modelling land-use change in economic simulation models. Section 2.4 concludes with several important themes in the literature, as well as important areas of future research.

Note that the majority of this review is concerned with reviewing the economic *impact* literature, which is not the same as studies on the *feasibility* of various biofuels and feedstocks (biomass inputs used in the fuel production process). Economic feasibility studies examine the cost of production characteristics of a specific biofuel production pathway. This area of inquiry is important for the research in this dissertation and a review of this literature, as well as methods for incorporating results into the analytical framework of this dissertation, is left to later chapters.

## 2.1 Overview

### 2.1.1 U.S. Biofuel Production

The biofuel industry in the United States has experienced a rapid expansion since 2000. While a small industry has existed since the late 1970's, production did not increase significantly until a series of economic and policy factors emerge in the early 21$^{st}$ century that created an environment supportive of the biofuel boom that is currently underway. Table 2.1 shows the history of domestic ethanol production, trade, and consumption since 2000. Domestic ethanol production has increased almost 750% over the past 12 years, with the vast majority of domestic production used for domestic consumption. However, a substantial export market has also developed in the past several years, with 2011 being the first year that U.S. ethanol exports to Brazil exceeded imports. In 2010 the United States was the world's largest producer of biofuels, accounting for 47.8% of global production (Energy Information Administration, 2012a). Brazil and Europe accounted for 28.4% and 13.4% of global production, respectively. Ethanol accounts for 82% of biofuel production globally, and 98% in the United States. Biodiesel, produced from vegetable oils (primarily soybean and palm) and animal fats, accounts for the non-ethanol share of global biofuel production.

Domestic ethanol production is highly concentrated in the Midwest (see Figure 2.1), in close proximity to the primary input, corn. The U.S. conventional ethanol industry is currently the largest consumer of the domestic corn supply, and has increased from consuming 10.5% of the annual harvest in 2002/03 to 40.3% in the 2010/11 harvest (USDA Office of the Chief Economist, 2012). Babcock and Fabiosa (2011) argue that the expansion of the industry was largely driven by large processing margins from 2005-2008 for ethanol refineries.

Table 2.1: U.S. Ethanol Production, Trade, Consumption, and Prices (Quantity data is in millions of gallons)

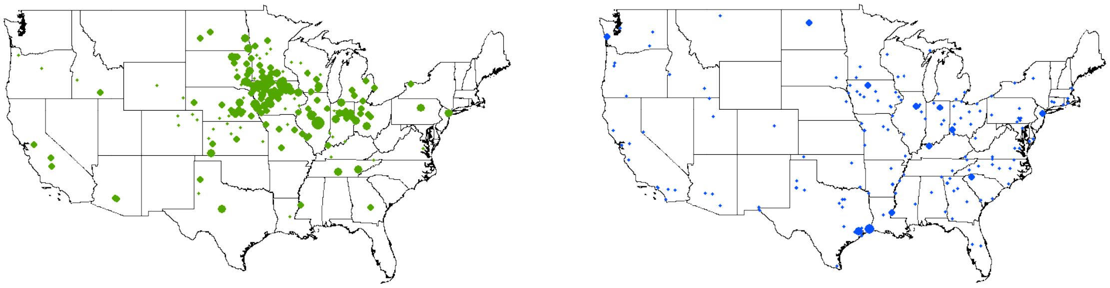
| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Domestic Production** [1] | | | | | | | | | | | | |
| | 1,630 | 1,770 | 2,130 | 2,800 | 3,400 | 3,904 | 4,855 | 6,500 | 9,000 | 10,600 | 13,230 | 13,741 |
| **Trade**[2] | | | | | | | | | | | | |
| U.S. Imports from: | | | | | | | | | | | | |
| Brazil | 10 | 4 | 8 | 12 | 112 | 72 | 453 | 225 | 247 | 66 | 78 | 166 |
| Carribean Nations | 60 | 43 | 46 | 61 | 70 | 103 | 167 | 239 | 292 | 177 | 7 | 100 |
| Canada | 10 | 12 | 11 | 9 | 12 | 12 | 21 | 22 | 15 | 26 | 27 | 19 |
| ROW | 74 | 91 | 60 | 87 | 33 | 18 | 66 | 18 | 16 | 11 | 11 | 6 |
| Total Imports | 154 | 151 | 125 | 169 | 227 | 206 | 707 | 504 | 571 | 280 | 121 | 292 |
| | | | | | | | | | | | | |
| U.S. Exports to: | | | | | | | | | | | | |
| Canada | 19 | 24 | 10 | 28 | 29 | 28 | 18 | 118 | 129 | 54 | 119 | 298 |
| Mexico | 14 | 14 | 17 | 21 | 6 | 4 | 2 | 1 | 2 | 2 | 19 | 29 |
| Brazil | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 23 | 396 |
| United Kingdom | 0 | 0 | 0 | 0 | 1 | 2 | 1 | 10 | 0 | 0 | 30 | 119 |
| UAE | 2 | 1 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 21 | 29 | 65 |
| Netherlands | 2 | 1 | 0 | 1 | 2 | 5 | 5 | 12 | 20 | 17 | 73 | 124 |
| Finland | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 12 | 44 |
| ROW | 16 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 29 | 10 |
| Total Exports | 53 | 46 | 30 | 50 | 39 | 45 | 27 | 142 | 150 | 96 | 334 | 1,084 |
| | | | | | | | | | | | | |
| **Domestic Consumption** | | | | | | | | | | | | |
| | 1,731 | 1,876 | 2,224 | 2,919 | 3,588 | 4,065 | 5,534 | 6,862 | 9,420 | 10,784 | 13,017 | 12,949 |
| **Ethanol Price**[3] | | | | | | | | | | | | |
| $/gallon | 1.35 | 1.48 | 1.12 | 1.35 | 1.69 | 1.80 | 2.58 | 2.24 | 2.47 | 1.79 | 1.93 | 2.70 |

[1] Renewable Fuels Association (2012)

[2] U.S. International Trade Commission (2012)

[3] Nebraska Ethanol Board (2012)

As a result, growth in total refinery production capacity increased by 92% from 2007-2009. On the demand side, high crude oil prices in the early 2000's made gasoline production more expensive and provided incentives for fuel blenders to search for low cost alternatives, such as ethanol. Demand for ethanol as a fuel oxygenate also increased over this same period as a result of many states banning the use of Methyl Tert-Buytel Ether (MTBE), previously the most predominant oxygenate fuel additive used in gasoline. These beneficial market factors were in addition to a substantive tax credit for blenders using ethanol (discussed below) in gasoline blends. While demand steadily rose, low corn prices prior to 2007 allowed ethanol refiners to produce at a relatively low cost since corn represents the largest variable cost in the ethanol production process. However, as corn prices began to increase to record highs (due to a variety of factors) and the 2008 global financial crisis brought about a precipitous decline in the price of crude oil and gasoline, ethanol processing margins in the U.S. decreased considerably. These economic conditions were a major factor in the lower capacity growth rates experienced from 2009 to the current day.



(a) Ethanol Production Capacity

(b) Biodiesel Production Capacity

Figure 2.1: U.S. Biofuel Production Capacity

With corn prices expected to stay high into the foreseeable future (Interagency Agricultural Projections Committee, 2011), growth in the industry is likely to be tied closely to growth in ethanol demand. Ethanol can be a complement to petroleum (as an oxygenate) or a substitute. However, the U.S. Energy Information Administration projects that gasoline consumption will remain relatively stable over the next 20 years, suggesting that the demand for ethanol as an oxygenate may be limited. Furthermore, the U.S. Environmental Protection Agency restricts ethanol use in gasoline to 10% (known as the "blend wall") due to vehicle performance and health issues.[1] The Energy Information Administration (2012b) has reported that U.S. ethanol production has reached the 10% blend wall. Stable gasoline consumption and current saturation of the oxygenate market implies that demand for ethanol as a motor fuel oxygenate is limited. Expansion as a fuel substitute is also possible with vehicles specifically manufactured to use higher ethanol blends, typically 85% ethanol (E85). Growing world demand for ethanol also presents a second possible source of demand-side growth for the industry. These factors, and policies that will be described below, have led to interest in alternatives to corn-based ethanol production, particularly fuels that use non-starch feedstocks, such as cellulosic biomass.

The U.S. cellulosic biofuel industry has not experienced the same boom as the conventional ethanol industry in the United States. Cellulosic biofuel is any biomass-to-liquid fuel production pathway derived from either the cellulose, hemicellulose, or lignin components of biomass (U.S. Environmental Protection Agency, 2012a).[2] This is reflective of the higher costs of producing a usable transportation fuel from cellulose and hemi-cellulose, especially in the conversion phase of the production process (Carriquiry et al., 2011). As of the writing of this dissertation, the U.S. Environmental Protection Agency has identified six

---

[1] The EPA has approved an increase in the blend wall to 15% for light-duty vehicles produced after 2001, although implementing this new level will still take several more years.

[2] For example, any biofuel derived from the stover of corn would be considered cellulosic biofuel, whereas biofuel derived from the corn grain itself is not since this component of the biomass is primarily starch.

Table 2.2: Projected 2012/2013 Cellulosic Biofuel Production in the U.S.

| **Company** | **Location** | **Capacity**[1] | **Feedstock** | **Fuel** |
|---|---|---|---|---|
| | | 2012 Projections | | |
| ZeaChem | Boardman, OR | 0.25 | Woody Biomass | Ethanol |
| American Process Inc. | Alpena, MI | 0.9 | Woody Biomass | Ethanol |
| KL Energy | Upton, WY | 1.5 | Woody Biomass | Biogasoline, Diesel |
| Fiberight | Blairstown, IA | 6 | MSW[2] | Ethanol |
| INEOS Bio | Vera Beach, FL | 8 | Ag Residue, MSW | Ethanol |
| KiOR | Columbus, MS | 10 | Pulp Wood | Biocrude |
| | | 2013 Projections | | |
| Bluefire Renewable | Fulton, MS | 19 | Wood Waste | Ethanol |
| Mascoma | Kinross, MI | 20 | Hardwood, Pulpwood | Ethanol |
| Poet | Emmetsburg, IA | 25 | Corn Stover | Ethanol |
| Abengoa | Hugoton, KS | 26.4 | Ag Residue, DEC[3] | Ethanol |

[1] Millions of Gallons [2] Municipal Solid Waste
[3] Dedicated Energy Crops

cellulosic biofuel facilities, shown in Table 2.2, that will be in operation in 2012 (U.S. Environmental Protection Agency, 2012a). Another 90.4 million gallons of capacity is expected to be added in 2013, including the first large-scale facilities using agricultural residues and perennial grasses. Ethanol will be the primary fuel produced in the early phases of industry development. Fuels other than ethanol, such as biobutanol and Fischer-Tropsch fuels, could become viable in the future. These fuels generally have higher energy content than ethanol and in many cases can be blended in gasoline as a direct petroleum substitute. They are also more compatible with existing fuel supply infrastructure (McKendry, 2002).

Carriquiry et al. (2011) report cellulosic ethanol production costs ranging from \$2.62-\$3.48/gallon of gasoline equivalent, depending on the conversion feedstock. These numbers reflect the break-even cost of producing the fuel, which implies a zero processing margin and little incentive to invest in new refineries. Even these break-even prices are higher than historic market ethanol prices, shown in Table 2.1, suggesting that without government support policies or changing market conditions, cellulosic ethanol penetration into the market is unlikely.

### 2.1.2 U.S. Biofuel Policy

United States biofuel policy has historically been a complex mix of economic instruments and other incentive programs put in place to encourage growth of a domestic biofuel industry and increased consumption amongst domestic consumers. Currently, only one industry-wide economic incentive is active: a biofuel consumption mandate. However, two others, a production tax credit for biofuel producers and an import tariff for ethanol, recently expired at the end of 2011.

The production tax credit, known formally as the volumetric ethanol excise tax credit (VEETC), was initially established in 1978 as part of the Energy Tax Act (Public Law 95-618) (Glozer, 2011). The size of the tax credit has ranged from 40-60¢/gallon, settling at 45¢/gallon for the majority of the biofuels boom in the early 21st century. The tax credit for corn ethanol officially expired in January 2012, as a result of a political atmosphere concerned with reducing government spending (Pear, 2012). The VEETC was modified as part of the 2007 Energy Independence and Security Act (EISA) to provide a higher tax credit for cellulosic biofuel ($1.01/gallon). This tax credit remains in effect.

The ethanol import tariff, originally enacted in the Omnibus Reconciliation Act of 1980, was designed to offset the taxpayer cost (financial not economic) of the ethanol tax credit, enacted two years prior (Glozer, 2011). Because the U.S. and Brazil are the world's largest producers of ethanol (producing 58% and 30% of global supply, respectively, in 2010), and have been for the past 10 years, the import tariff also serves the objective of protecting the U.S. biofuel industry from foreign competition. While somewhat effective, loopholes have been exploited using the Caribbean Basin Initiative (CBI), allowing Brazilian ethanol to enter the U.S. duty free if it is first passed (and partially processed) through a tariff-exempt nation (primarily Costa Rica, Jamaica, and El Salvador) (Yacobucci, 2005). In fact, the vast majority of ethanol imported into the United States (Table 2.1) originates in Brazil. Combined with the tax credit discussed above, the additional import tariff has essentially required foreign ethanol to have a $1.00/gallon lower cost than domestic ethanol in order to compete in the U.S. market. While the import tariff expired at the end of 2011, along with the production tax credit, these two policies have assisted in insulating the domestic ethanol market from foreign competition.

A biofuel consumption mandate, commonly referred to as the Renewable Fuel Standard (RFS), is the third major economic biofuel policy in the United States. The RFS was originally established as part of the 2005 Energy Policy Act (EPAct), and later amended in the 2007 Energy Independence and Security Act (EISA) (U.S. House of Representatives 110th Congress, 2007). The original RFS, legislated in the EPAct, set volumetric requirements for the 2006-2012 time frame. EISA amended these volumetric requirements for 2010-2012 and set future consumption mandates through 2022. The amended legislation is commonly referred to as “RFS2”. The legislation requires the U.S. Environmental Protection Agency to establish regulations for ensuring that the annual volumetric production requirements set in EISA be met (U.S. Environmental Protection Agency, 2012b). There are several critical components of the EISA legislation worth noting. First, the mandate follows a three-tiered structure. As the first tier, total biofuel consumption quantities are established. The second tier requires that of this total mandate, a specific percentage each year must come from ‘advanced’ biofuels, defined as any renewable fuel other than ethanol derived from corn starch, subject to the sustainability criteria described below. Also in the second tier, a mandate is set each year for biodiesel consumption. The third tier requires that the advanced biofuel target must contain a specific percentage of 'cellulosic' biofuel, defined as any renewable fuel that is derived from cellulose, hemi-cellulose, or lignin (ie, non-starch components of the biomass feedstock). The mandates, as established in the two laws, are shown in Figure 2.2.

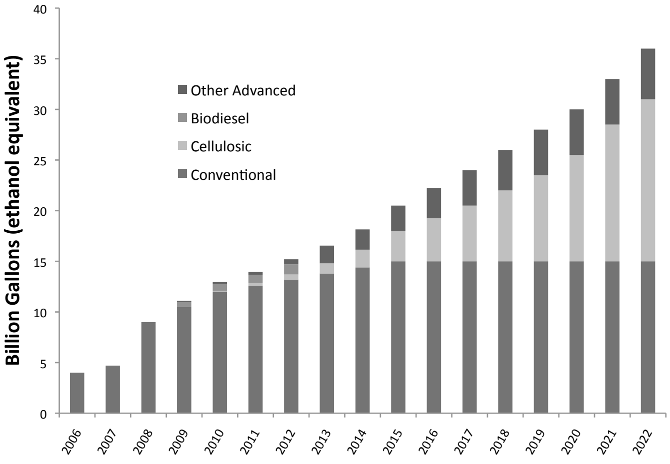


Figure 2.2: U.S. Renewable Fuel Standard: Volumetric Mandates by Category

A second important feature of the EISA legislation was the addition of a set of sustainability criteria for all eligible biofuels. This criteria sets greenhouse gas reduction requirements for conventional, advanced, and cellulosic biofuels, requiring that life-cycle emissions be 20%, 50%, and 60%, respectively, below the life-cycle emissions of conventional gasoline. However, EPA only approves generic 'pathways,' rather than tracking and verifying the life-cycle emissions of each gallon of fuel consumed.

A final caveat of the program is that EPA has the authority to reduce the mandated quantities in any given year if the agency believes that the industry is not capable of producing the volumes required in the legislation. In fact, since 2010 (the initial year of the cellulosic biofuel mandate), EPA has reduced the tier 3 mandate each year by over 93%.

Under the RFS, any industrial facility that refines or imports gasoline is treated as a regulated entity and is required to prove that they consume a specified level of renewable fuel each year. This regulation applies primarily to petroleum refineries, although technically any industry that produces gasoline is also subject to the renewable fuel requirements. The program is implemented using a system similar in structure to the $SO_2$ cap-and-trade program. For each qualifying batch of biofuel produced, a Renewable Identification Number (RIN) is assigned that certifies the type of fuel and its production history. Gasoline blenders are required to submit a specified number of RINs to the EPA each year in compliance with the RFS. RINs can be obtained by either purchasing the biofuel directly, or through purchases of excess RINs from other blenders in a market. If the mandate is binding, a "wedge" is created between the supply and demand for the fuel, and the RIN price should converge to this difference and provide incentives to manufacture these fuels.

Figure 2.3 provides a graphical representation of the RIN program, assuming a perfectly competitive compliance market. If the mandate for biofuels, M, is less the biofuel market equilibrium quantity (Q*), the mandate is non-binding and the RIN price is zero. However, for M>Q*, a financial incentive is needed to bridge the gap between the marginal cost of producing the $M^{th}$ unit, and the value of that unit. This is shown as the wedge between biofuel supply and demand at quantity M (a), and is the value of the RIN, $p^{\mathrm{RIN}}$. The supply of RINs (b) and the theoretical equilibrium price, therefore depends on the mandated level, shown in the graph as supply curve $S^{\mathrm{RIN}}$. For each category in the mandate, a unique RIN market is established in order to provide the financial incentives for producing a specific type of biofuel. For example, if the conventional corn ethanol mandate is non-binding (due to economic factors), but the marginal cost of producing cellulosic ethanol exceeds the unit price, transactions would be expected to occur in the cellulosic RIN market but not in the conventional RIN market. The market clearing RIN price will be unique for each category of biofuel. Mcphail et al. (2011) and Thompson et al. (2010a) discuss the RIN program in greater detail and provide historical RIN market data. They show that in the conventional ethanol market, RIN prices have converged at 1-3¢/gallon, suggesting that the mandate is essentially non-binding. For biodiesel, 2010/11 RIN prices varied from \$0.80-1.60/gallon, which suggests that the RFS had an important role in expanding the industry. Cellulosic production volumes have yet to reach a level where a viable RIN market exists. With the expiration of the tax credit and import tariff, the Renewable Fuel Standard is for now the primary economic policy instrument in place to provide incentives for biofuel production.

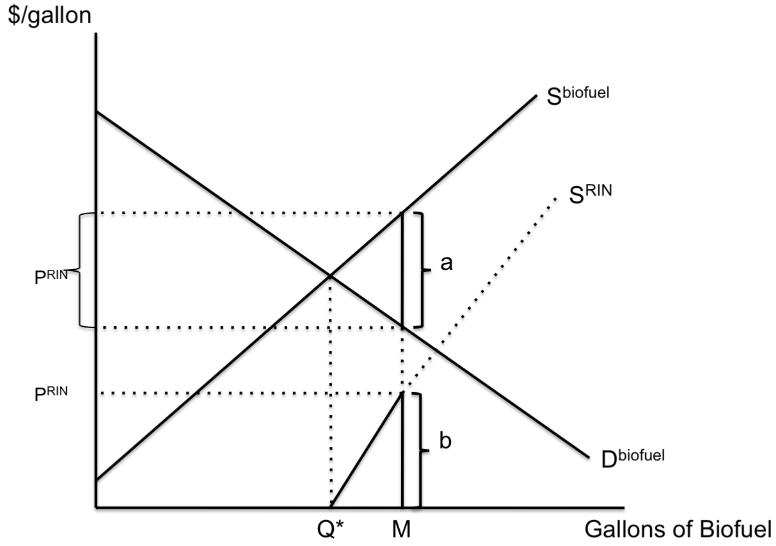


Figure 2.3: Market for Biofuels and Renewable Identification Numbers

Additional incentives, such as federal loan guarantees, production tax credits for cellulosic feedstocks, and grant programs have also contributed to the favorable policy environment for the U.S. biofuel industry. See Glozer (2011) for a comprehensive review of these other programs.

## 2.2 Commodity Market Impacts of Biofuel Production

Biofuel production in the U.S. is often promoted as an avenue for decreasing reliance on foreign oil imports, decreasing greenhouse gas emissions, and improving rural economic development (see National Research Council, 2011, for a discussion). A large body of literature has developed exploring both the costs and benefits of biofuel production, and the majority of the economics literature to date has focused on conventional ethanol production. An interesting subset of this literature has focused on the unintended consequences of the growing biofuels industry, focusing in particular on the effects of diverting land away from producing food and feed commodities.

The commodity market impacts of expanding biofuel production have been addressed in the literature from a variety of perspectives. The original studies in this field focused on the "food/fuel" tradeoff and examined the relationship between biofuel production and non-fuel uses of agricultural commodities. A subset of this literature has focused especially on livestock sector impacts. Several studies have focused on the impacts of biofuel production in transportation fuel markets. Finally, an important body of literature has developed examining the welfare effects of biofuel policy, which in many ways links (or motivates) these previous strands in the literature. In this section, each of these important themes in the overall biofuel impact literature is considered.

### 2.2.1 Agricultural Commodity Market Impacts

Much of the impact literature in economics has stemmed from concerns that biofuel production causes large increases in agricultural commodity prices. The concurrence of the 2007-2008 global agricultural price spike with escalating biofuel production levels caused many to question whether a causal link existed between the two (Runge and Senauer, 2007). Rajagopal et al. (2007) develop a simple analytical framework for showing the food/fuel tradeoff, arguing that increased biofuel production benefits agricultural producers and gasoline consumers, and harms agricultural consumers in the short run. While they find that an ethanol subsidy is justified in terms of the cost-benefit tradeoff, the equity effects suggest that biofuel production could threaten food security while providing benefits primarily to relatively wealthier fuel-consumers. This tradeoff is shown graphically in Figure 2.4 (adapted from Rajagopal et al. (2007)) and provides a conceptualization for many of the market-induced impacts of expanding biofuel production. Variables denoting total market supply/demand are capitalized, and variables for specific industry demand are in lower case.

In the market for corn, prior to a biofuel expansion, corn use for biofuel (bf) and non-fuel (nf) uses of corn (feed, exports, etc) are determined at the market clearing price, $\mathrm{p}^0$, where total corn supply $\mathrm{S}^{\mathrm{corn}}$ is equal total market demand $\mathrm{D}^{\mathrm{corn0}}$. This market demand is the horizontal sum of the biofuel ($\mathrm{d}^{\mathrm{b0}}$) and nonfuel ($\mathrm{d}^{\mathrm{nf}}$) sectors. At this price, the total corn harvest, $\mathrm{Q}^{T0}$, is allocated to ethanol demand, $\mathrm{q}^{b0}$, and non-fuel uses, $\mathrm{q}^{nf0}$. An exogenous increase in biofuel demand, due to market or policy forces, shifts the demand curve for corn (fuel uses only) from $\mathrm{d}^{\mathrm{b0}}$ to $\mathrm{d}^{\mathrm{b1}}$, which in turn increases market demand for corn from $\mathrm{D}^{\mathrm{Corn0}}$ to $\mathrm{D}^{\mathrm{Corn1}}$. The allocation of the new equilibrium corn quantity, $\mathrm{Q}^{T1}$, to biofuel, $\mathrm{q}^{b1}$, and other uses, $\mathrm{q}^{nf1}$, shows that increased biofuel production crowds out non-fuel uses. This result depends in large part on the elasticity of supply for corn and the elasticity of demand for non-corn uses. More inelastic supply will induce a larger price response in the corn market, resulting in larger changes in the quantity demanded for non-fuel uses. More inelastic non-fuel demand implies larger price fluctuations in the non-fuel markets that use corn as an input. As an example, consider the effect on livestock markets. Corn is used as a feed input in both the ruminant (dairy and beef) and non-ruminant (poultry and pork) livestock industries. Demand for corn is more inelastic in the non-ruminant livestock industry because there are not as many suitable feed substitutes for corn; whereas, feed rations can be altered more easily for ruminant livestock. For any given biofuel expansion, we would expect larger price effects in the non-ruminant livestock industries, which in turn are likely to be passed on as higher final processed food product prices. This logic applies to any market that competes directly with biofuel for agricultural inputs, and because agricultural land markets link all agricultural commodities, the market-induced effects move beyond the market for corn.

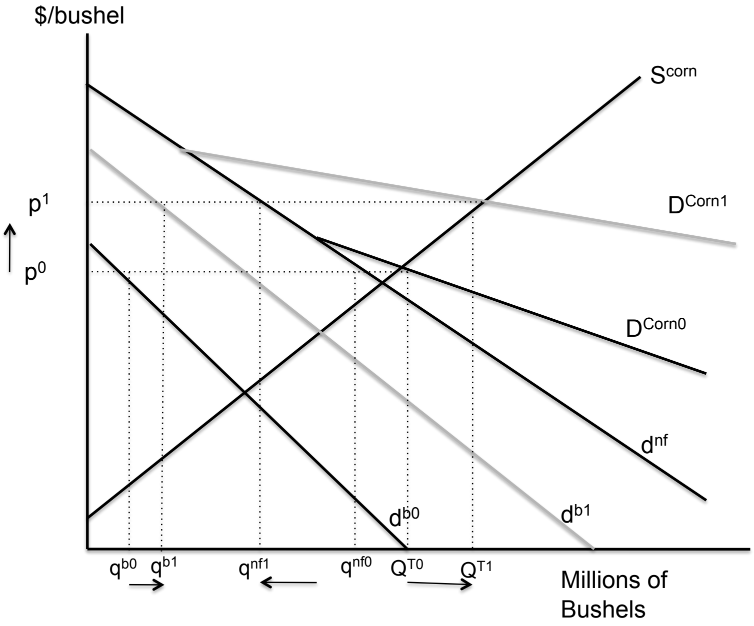


Figure 2.4: Impacts of a Biofuel Expansion on the Corn Market

Early research in this area focused on the transmission of biofuel policies to other agricultural commodity markets, both domestic and global. Using a global partial equilibrium model developed at the International Food Policy Research Institute, Rosegrant et al. (2008)

conduct a detailed simulation experiment on the link between biofuel production and global agricultural commodity prices. The authors find that expanding global biofuel production according to existing government mandates and subsidies could lead to global price increases for corn, wheat, and oilseeds of 18%, 8%, and 12%, respectively. Under a more aggressive biofuel expansion scenario, prices for these three commodities are projected to increase 72%, 20%, and 44%, respectively. These results are not encouraging for biofuel proponents. A later study, using the same model, found the price effects to be much more modest, only 3.5% for all cereal grain markets (Msangi et al., 2010). The differences appear to be due primarily to assumptions regarding yield improvements and demand growth in developing countries. Rosegrant et al. (2008) and Msangi et al. (2007) (a nearly identical study from the same group) were two of the first studies on this topic and raised serious concern about the food/fuel tradeoffs of national biofuel production strategies.

Other studies exploring the biofuel food price linkage have found impacts on the order of the Msangi et al. (2010) study (although rarely do any two studies measure exactly the same scenario). Ferris and Joshi (2010) use an econometric model of the U.S. agriculture industry and find that increasing corn ethanol and biodiesel production by 27% and 66%, respectively, caused a 5.8% increase in the domestic food price index. Using a partial equilibrium (PE) model developed jointly by the Center for Agriculture and Rural Development (CARD) at Iowa State University and the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri, Hayes et al. (2009) find that a $1/bushel increase in the price of corn increases the domestic food price index by 0.8%.[3] The impact of ethanol

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[3] Hayes et al. (2009) is one example of the annual CARD/FAPRI *U.S. and World Outlook* reports issued by the institutes. Previous CARD/FAPRI outlooks have also examined the impacts of biofuel production on agricultural markets and are available through the FAPRI website.

production on domestic corn prices, according to the authors, is slightly less than $1/bushel. Fabiosa et al. (2010b) reviews several other studies using the same CARD/FAPRI PE model, focusing particularly on the transmission of domestic agricultural commodity price changes to international markets. While they do not directly report price changes, their results show that global corn and sugar markets are fairly responsive to increased ethanol production. This study highlights a general trend in the global impact assessment literature of not directly addressing questions of welfare changes due to biofuel expansion. While an admittedly difficult task, connecting changes in global commodity markets to country-specific welfare measures is an important area of future work.

While the link between biofuel production and higher agricultural commodity prices is surely present, the above studies suggest that at current production levels the food/fuel tradeoff may be relatively minor. In fact, several recent studies have suggested that other factors were largely driving the 2007-2008 global food price crisis, including short-term conditions such as high energy prices, adverse weather events, domestic policy restrictions on agricultural trade, and speculative investment, as well as long-term drivers such as growing demand in developing nations (Pfuderer and del Castillo, 2008; Baffes and Haniotis, 2010). Searchinger (2011) provides an alternative theory, although largely conceptual and untested, that biofuel demand has limited the ability of the global agricultural system to response to short-term market shocks, which in turn exacerbates any price volatility that otherwise would have been relatively minor.

The partial equilibrium and econometric studies cited above do not include general equilibrium effects that may be important in estimating the food/fuel tradeoff of conventional biofuel production. In general, Kretschmer and Peterson (2010) note that general equilibrium studies of biofuel expansion tend to report smaller effects on agricultural commodity markets. This is primarily due to the fact that the assumed agricultural commodity supply elasticities tend to be more elastic in general equilibrium models. Also, because there are more sectoral interactions and income effects included in general equilibrium studies, impacts are likely to be distributed more broadly throughout the economy.

Several studies of biofuel expansion have used the general equilibrium model developed by the Global Trade Analysis Project (GTAP) at Purdue University. Hertel et al. (2008) model a global biofuel expansion, focusing on policy incentives in the United States and the European Union. While they do not directly report price changes, they find that output of non-bioenergy crops drops considerably in the U.S., EU, and Brazil. They attribute this to a negative supply response due to higher cropland values, which implies an increase in agricultural commodity prices. Taheripour et al. (2010) note an important limitation of this original study in that it did not include the mitigating effect of incorporating dried distillers grains with solubles (DDGS), an ethanol production by-product, into the modelling framework, which then enters the livestock market as a feed substitute. They find that including these byproducts reduces the impact of biofuel production on global agricultural commodity prices by approximately 20% for most commodities in most regions. This is due to the fact that the recycling of DDGS into the global feed complex reduces the amount that biofuel demand for agricultural inputs displaces demand from feed industries. Finally, Keeney and Hertel (2009) integrated much of the GTAP general equilibrium modelling work into a comprehensive analysis, resulting in a seminal paper in the biofuel impact assessment field. This paper produced two additional insights that in many ways highlight the uncertainty and difficulty of capturing changes in international commodity markets.

The authors integrate two key behavioral responses into the global CGE model, a yield-crop price response and an acreage-crop price response. They show that the impacts of expanding biofuel production are largely driven by assumptions made regarding the parameterization of these two effects. Because the study focused more on land-use change issues, rather than impacts on commodity markets, further discussion is left to Section 2.3 of this chapter.

Other general equilibrium studies using a very similar approach to GTAP have reported similar price effects. Timilsina et al. (2010) model a global biofuel expansion (similar to Hertel et al., 2008) and find that global corn prices increase 1.1-3.7%, wheat prices increase 1.1-2.4%, and oilseed prices increase 1.5-3.1%. Gurgel et al. (2007) report an increase in the global food price index of 5%, although this is over a 100 year time horizon. The price effects in the near term are virtually non-existent. Several studies have used a general equilibrium framework to focus specifically on the impacts of European Union biofuel production mandates (for an overview of national biofuel policies see Sorda et al., 2010). Britz and Hertel (2011) find that the mandates have a major effect on EU oilseed markets, increasing price by almost 50%. The effect on other commodity prices is largely mitigated by a global expansion of agricultural land. Banse et al. (2008) report increases in global oilseed and cereal prices of 8% and 5.5% respectively, if the EU mandate is met.

Comparing results across studies is difficult. Kretschmer and Peterson (2010) attempt to review and compare the findings in the biofuel impact assessment literature (focusing on agricultural commodity market effects), but do not standardize the various assumptions and scenarios in each study. Such an exercise may be useful for comprehensively reviewing the literature; however, because each modelling framework is unique and extremely complex, such a task, in practice, may be infeasible. In general, predictions from general equilibrium models of the distorting effects on agricultural commodity markets tend to be quite small.

Very few studies have examined the price effects of advanced biofuels that use cellulosic feedstocks. Campiche et al. (2010) examines the impact of enzyme cost on cellulosic biofuel production and subsequent effects on U.S. agricultural commodity markets. The analysis only considers the effect of cellulosic ethanol using corn stover, which may significantly underestimate the impacts of the emerging advanced biofuel industry since stover is an agricultural residue that does not compete for land with other commodities. In a recent working paper, Taheripour et al. (2011a) adapts the GTAP modelling framework to consider biofuel production from switchgrass, miscanthus and corn stover. Their analysis in many respects parallels the work presented in Chapter 4 and is a useful benchmark for the results presented there. The food/fuel tradeoff is not a primary objective of that study, and therefore a further review of Taheripour et al. (2011a) is left to that chapter in order to provide a more appropriate context.

While the food/fuel tradeoff is perhaps one of the most contentious issues surrounding biofuel production, much of the academic literature suggests that market effects may be quite small. This could be due to correctly predicting the global economy's ability to respond to changing patterns of agricultural commodity trade. However, it could also be due to the narrow scope of the individual studies, which primarily consider the global impacts of a specific region's biofuel expansion. Aggregating over all of the various national policies may reveal much larger price impacts in global agricultural commodity markets. One might also argue that biofuel production creates a paradigm where food security and energy security could become conflicting policy objectives. Kahrl and Roland-Holst (2010) address this from an global equality perspective, noting that food security is largely regressive in income, while energy security is largely progressive in income. This insight (initially considered in Rajagopal et al., 2007) suggests that national interests between developed and developing nations are less likely to align and as land resources become scarcer, a greater tension may exist centered around the food/fuel tradeoff.

### 2.2.2 Effects on Livestock Markets

Historically, the U.S. feed complex has been the largest consumer of corn, and therefore the impacts of biofuel production on agricultural commodity prices has the potential to cause significant changes in the production structure of the livestock industry. The industry has generally argued against government support for conventional biofuel production due to the potential to increase the price of corn (American Meat Institute, 2010). However, only a very small body of the peer-reviewed biofuel impact assessment literature has focused on this linkage.

Hayes et al. (2009) use the CARD/FAPRI partial equilibrium model of the U.S. agricultural sector to determine the impacts of domestic biofuel production on livestock markets. They find almost no effect on the net returns in the beef, dairy, pork, and poultry markets. Any increases in input costs are passed on to consumers in slightly higher prices, with no net impact on the industry. These results suggest that in the medium to long-run, the livestock industry is able to adapt quite well to a restructuring of corn and soybean markets due to increase biofuel demand. The industry's objections may therefore be largely a concern about short-term effects in the market, as producers are required to make adjustments to higher corn prices. No academic studies were found explicitly exploring the short-term effects of biofuel production on livestock markets.

Using a general equilibrium modelling framework, Gohin (2008) assesses the impact of European Union biofuel mandates on regional livestock markets and find that the mandates have very little impact on either production levels or market prices. Taheripour et al. (2011a) use a similar modelling approach but extend the analysis to factor in U.S. biofuel production and the impacts on global livestock markets. While they also find that impacts in biofuel producing regions are minimal, the transmission of higher commodity prices has a major impact on livestock markets outside of biofuel producing regions. In addition to higher feed prices, land competition for biofuel feedstocks increases land rental rates globally and increases the opportunity cost of using grazing land for livestock production. This effect is largely driven by the assumption that only biofuel producing regions are able to take advantage of the increased supply of dried distillers grains with solubles in the domestic feed composition. By allowing for greater feed substitution possibilities, especially for ruminant livestock, increases in overall feed prices are somewhat mitigated. This result is somewhat questionable given the recent emergence of a global market for DDGS. In fact, U.S. exports of DDGS has increased dramatically in the past several years, with demand from China, Mexico, and Canada accounting for the majority of U.S. exports (U.S. International Trade Commission, 2012). As the ethanol industry expands globally, these emerging trade patterns will be an important factor in understanding the impact of biofuel production on global livestock markets.

A second important area of emerging research in this field examines the ability to integrate biofuel coproducts, DDGS, into the livestock feed composition. Beckman et al. (2011) note that feed substitution patterns under expanding biofuel production scenarios has been an understudied area of inquiry in the biofuel impact assessment literature, where even the most comprehensive studies use simplistic assumptions regarding the livestock industry's ability to incorporate DDGS into the feed complex. They argue that as the ethanol industry has grown, livestock producers have responded by incorporating higher DDGS levels in feed mixes as an energy substitute, which counters the standard hypothesis that producers use DDGS as a protein substitute. Furthermore, they find that there is considerable heterogeneity in DDGS quality making feed composition ratios a function not only of agricultural commodity prices, but also feed input quality. Understanding these behavioral patterns and constraints in non-biofuel producing regions could potentially effect the broader impact of biofuel production on agricultural commodity markets.

### 2.2.3 Effects on Global Transportation Fuel Markets

Several studies have focused specifically on the impact of expanded biofuel production on global oil markets. This is an especially important topic in the biofuels literature because it directly addresses certain behavioral phenomenon that may impact the efficacy of bioenergy production as a greenhouse gas mitigation strategy. The conventional policy rationale for biofuels as a GHG emissions reduction strategy states that increased biofuel production will displace oil in gasoline blends. Because emissions from biofuel combustion are offset by $CO_2$ sequestration in the feedstock growing phase, the net GHG emissions (excluding land-use change effects) are projected to be lower than conventional gasoline (Farrell et al., 2006). However, Hochman et al. (2010) argue that a portion of this mitigation potential could be offset by a 'rebound effect' in global transportation fuel markets. Using a partial equilibrium model of the world fuel market (factoring in market power in OPEC nations), the authors show that the introduction of biofuels into the global market crowds out fossil fuels, but also lowers the price of gasoline (a composite blend of petroleum and biofuels). The lower world price for transportation fuel causes global fuel consumption to increase (the rebound effect), which in turn offsets some of the intended emissions savings of a biofuel policy. The authors conclude that net emissions following a biofuel boom depend on the petroleum supply elasticity. Other empirical estimates have shown that the biofuel production rebound effect can be quite large. For example, Drabik and de Gorter (2010) find that each gallon of ethanol produced only displaces 0.2-0.3 gallons of petroleum. Thompson et al. (2011) estimate that reducing biofuel production in the U.S. by one gallon induces a 0.3 gallon decrease in gasoline consumption outside the U.S., which implies that the rebound effect of *increasing biofuel production* is approximately 0.3 gallons of gasoline for every gallon of biofuel. As Hochman et al. (2010) notes, the biofuel rebound effect is of interest only with regards to the greenhouse gas implications, as changes in fuel consumption generally is not an important economic issue.

Rajagopal et al. (2011) further develop the rebound effect concept, as it relates to biofuel production, renaming the phenomenon “’indirect fuel-use change” (iFUC). In addition to developing a simple theoretical model of the iFUC phenomenon, they show that U.S. biofuel mandates unambiguously increase fuel consumption outside of the United States. However, on net, global oil consumption (including the United States) declines in the presence of biofuel mandates. In fact, the authors show that the iFUC effect actually amplifies the GHG *benefits* from biofuel production by 75%. For example, these results suggest that in terms of greenhouse gas emissions, each gallon of biofuels produced replaces 1.75 gallons of petroleum. This result directly contradicts the findings reported above (including those by the same authors in Hochman et al. (2010)). The authors note this result should not be considered authoritative (due to the simplicity of the model used), but rather is useful in showing how behavioral assumptions in domestic and global fuels markets can affect the overall greenhouse gas footprint of biofuel production. They also argue that phenomenon such as iFUC are equally as likely as market-induced land-use change (discussed below), and should therefore be considered in policy and regulatory discussions.

### 2.2.4 Welfare Effects of U.S. Bioenergy Policy

This section focuses on a strand of literature that explores the welfare effects of U.S. bioenergy policies. These studies differ from those above in that they explicitly model the policy instruments, as opposed to modelling the impacts of an exogenous increase in biofuel production. By more formally modelling the instruments, these studies are also able to explore the economic effects of interacting bioenergy policy with existing agricultural and energy policies.

Several studies have developed formal theoretical models analyzing the impacts of the 45¢/gallon ethanol production tax credit (VEETC). Gardner (2003) applies a simplified partial equilibrium model of the U.S. corn and ethanol sectors, showing that the ethanol subsidy induces a wealth transfer from U.S. taxpayers and non-ethanol corn users to ethanol and corn producers. Consumers in the fuel market also benefit as the subsidized supply of ethanol lowers blended gasoline prices. However, the benefit to corn growers, which is often used as a justification for the subsidies, can be quite minimal when a deficiency payment program is also in place. de Gorter and Just (2007) build upon this basic analysis and develop a more rigorous welfare framework for analyzing the tax credit. They find similar wealth transfer results. However, when interacted with other farm support programs, they find sizable policy redundancies and show that much of the ethanol tax credit is not passed on to corn producers. This redundancy adds to the traditional measure of Harbinger deadweight loss, resulting in what the authors call ‘rectangular’ deadweight loss (or ’water’ in the subsidy). Factoring in these inefficiencies has the effect of increasing the deadweight loss of the tax credit by over 600%. These two studies suggest that the tax credit can clearly benefit the ethanol industry and consumers of transportation fuels. The effects on food consumers (both foreign and domestic) is unambiguously adverse, although the magnitude of the welfare loss is dependent on the degree to which the ethanol subsidy increases the price of corn. The rural development benefits could also be considerable, but only in the absence of other support programs. Factoring in the existence of these alternative price and income support programs makes to benefits to corn producers negligible.

The second set of studies in this section analyze the welfare effects of the U.S. ethanol import tariff (set at 54¢/gallon before its recent expiration). Martinez-gonzalez et al. (2007) econometrically estimate the import demand and export supply functions for the United States and Brazil, respectively, which accounts for the existence of both the U.S. import tariff and tax credit. Using these elasticity estimates they develop a simple two-nation partial equilibrium trade model and project the welfare effects of removing the import tariff. They predict total deadweight loss to decline by approximately $80 million if the tariff is removed, split evenly between the U.S. (consumer surplus for ethanol consumers) and Brazil (producer surplus for ethanol producers). This value increases considerably as the U.S. consumption mandate expands and lower cost Brazilian ethanol satisfies a large fraction of U.S. demand.[4] Using the CARD/FAPRI partial equilibrium model, Elobeid and Tokgoz (2008) and Kruse et al. (2007) simulate the effects on world ethanol markets of removing the U.S. tariff and ethanol tax credit. Both studies find that the existing support policies

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[4] Recent market developments have reduced the cost gap between U.S. and Brazilian ethanol production, suggesting that the findings of this study may not be appropriate for forward looking analysis.

are effective in insulating the U.S. ethanol industry from trade competition, and removing the tariff would decrease the world price of ethanol. U.S. ethanol imports would increase, primarily from Brazil, while domestic production declines. Elobeid and Tokgoz (2008) find that removing only the tariff increases consumer surplus and reduces producer surplus in the U.S. ethanol market. Removing the tariff and the tax credit reduces both consumer and producer surplus in the ethanol market. Consumer surplus declines because the price of ethanol (and therefore blended gasoline) is no longer subsidized by U.S. taxpayers. According to these two studies, overall welfare gains are experienced when only the trade distortions are removed. de Gorter and Just (2008) argue that the approach of the above studies is flawed because of the complex interactions of the three biofuel policies. The authors find that in the presence of tax credits and the RFS' binding quantity mandates, removing the import tariff has little effect on U.S. ethanol prices (and therefore producer and consumer welfare). This is due to the fact that the RFS creates a price premium for U.S. ethanol, which supports the high prices experienced if the tariff were still in effect. World ethanol prices increase though if the tariff is removed.

Finally, several studies examine the welfare implications of the U.S. Renewable Fuel Standard. Intuitively, we would expect that a blending mandate would increase the price of blended gasoline as the higher cost biofuel is passed on to fuel consumers. This differs from a production subsidy where the higher cost of biofuel is paid by the taxpayer, and therefore gasoline consumers are effectively subsidized and experience welfare gains. de Gorter and Just (2009) show, however, that this logic is not entirely accurate. A production mandate can either increase or decrease the consumer price of fuel, depending on the elasticity of demand for gasoline (without biofuel) relative to the elasticity of demand for biofuel. The mandate has two effects on the price of the final transportation fuel. The first effect increases the price of fuel since biofuel tends to be more expensive than gasoline on a per energy basis. The second effect decreases the price of fuel since gasoline demand declines due to being replaced by biofuel. Whichever of these effects is stronger (dictated by the relatively demand elasticity of gasoline to biofuel) will determine whether the final fuel price increases or decreases, and therefore the degree to which fuel consumers pay for biofuel production mandates. Empirical results show fuel price movements in both directions depending on the year. Rajagopal et al. (2007) estimate that fuel prices have dropped as a result of the production mandate.

One important limitation of the de Gorter and Just (2009) study is the assumption that biofuel and gasoline are perfect substitutes. Ando et al. (2010) relax this assumption and find that in the short-run the overall price of fuel is likely to decrease slightly as a result of the blend mandate. This increases consumer surplus in the U.S. transportation fuel market, as well as producer surplus for ethanol producers. Producer surplus declines for gasoline producers. They find that total welfare declines, even after factoring in greenhouse gas benefits from biofuel consumption. In the long-run, as gasoline supply is more elastic, fuel prices increase overall, and the same welfare results hold except that consumer surplus declines relative to the short-run scenario.

Roberts and Schlenker (2010) extend the analysis beyond domestic markets and examine the welfare effects of the U.S. production mandates on food consumers globally. They find that the U.S. production mandate, in addition to ethanol price supports, increases global food prices by 30% resulting in a large decrease in global consumer surplus. They also suggest that the reported price increase is mitigated substantially by a large supply response in global agricultural markets. The authors are not able to distinguish between the effects of the mandate and the effects of the tax. For global food prices, we would not expect the composite effect of the two policies to differ much proportionally from the additive effects of each policy individually since both policies should have similar effects on U.S. corn markets. Lowering the subsidy would simply result in a higher RIN price, and the effect on agricultural commodity prices is unlikely to change significantly.

### 2.3 Biofuel Production Impacts on Land Use Change

This section outlines the literature on the relationship between biofuel production and land-use change. This relationship is critical to understanding the market-mediated impacts of biofuel production. Land availability for bioenergy feedstocks is the key factor in measuring the second-order effects, largely adverse, from biofuel production. Several studies have shown that the physical availability of land for biofuel feedstock production is more than sufficient to meet both domestic and global biofuel production objectives (see for example Hoogwijk et al., 2003; Kim and Dale, 2004; Campbell et al., 2008; Cai et al., 2011; Perlack and Stokes, 2011); however these studies often do not account for economic factors involved in the land allocation decision.

Structural simulation models are the most common approach to analyzing the impacts of reallocating and expanding the land base for bioenergy feedstock production. This section will consider general equilibrium and partial equilibrium studies separately. There are two effects in the land allocation decision that drive the second-order impacts of bioenergy production on local, regional, and global agricultural commodity markets. First is the effect of displacing conventional agricultural commodities on existing cropland (defined as the 'intensive' land margin). Second is the effect of expanding total cropland acreage to either grow bioenergy feedstocks directly or grow crops displaced by bioenergy feedstock production (defined as the 'extensive' land margin). Modelling and parameterizing these intensive and extensive margin changes is an active area of current research.

Land-use change resulting from biofuel expansion has become a focal point in the discussion on biofuel impacts. Both the food/fuel tradeoffs described above and greenhouse gas emissions from terrestrial ecosystem conversion are driven by land supply responses amongst economic agents. Models used for biofuel impact analysis often incorporate a wide variety of economic behavior; however, the link between food and fuel markets is largely reliant on assumptions about land transformation, at both the intensive and extensive margins. This topic will become increasingly important as inquiries are made into the ecosystem service impacts of bioenergy feedstock production. The bioenergy literature to date has made a distinction between two types of land use change: direct and indirect. While definitions tend to vary somewhat across studies, direct land-use change is assumed to refer to the direct displacement of a parcel of land for bioenergy feedstock production. Taking an acre of wheat out of production in order to grow corn for ethanol is direct land-use change. Indirect land-use change (iLUC) effects are assumed to be second-order changes in land-use due to market-mediated responses from biofuel expansion. If diverting land to switchgrass increases domestic land rents and this in turn causes pastureland to be converted to wheat production, this is considered an indirect effect. Economists have contributed a great deal to the literature on indirect land-use change, as economic equilibrium models are well-suited for addressing questions of second-order market-mediated impacts.

The theoretical literature on land-use change resulting from biofuel expansion is limited. Feng and Babcock (2010) develop a theoretical model to evaluate the impacts of expanding

U.S. biofuel production on cropland intensification, allocation of existing cropland amongst crops, and cropland expansion. While they find, intuitively, that a price increase for a given crop will increase land allocated to the production of that crop, the cross price effects on acreage allocation to non-bioenergy crops is more complex. If the bioenergy feedstock and conventional crop are substitutes in production, due to competition for land in a given season for example, they find that an increase in the price of crop $a$ will lead to more intensive management of that crop (increasing land share or fertilizer intensity). While if crops are complements in production, due to the need for multi-crop rotations, the extensive margin effect dominates. Conventional biofuel feedstocks, such as corn, have characteristics of both substitutes and complements in production, whereas perennial grasses are not grown in rotation with conventional commodities. We would therefore expect that expanding the production of dedicated energy crops such as miscanthus or switchgrass would first crowd out conventional crop production before expanding onto marginal lands. These effects, developed theoretically, are important to keep in mind when considering the results of the structural models described below, a task to which we will now turn.

### 2.3.1 Land Allocation in General Equilibrium Models

General equilibrium models have evolved over the last two decades to address questions of land allocation in response to economic drivers in agriculture and energy markets. More recently, a body of literature has developed that explores the effect of biofuel production on acreage allocations, primarily at a global or regional scale. Two groups have led the way in these modelling efforts, and the model presented in Chapter 3 is in the tradition of these models. The Global Trade Analysis Project (GTAP) at Purdue University, developed and directed by Thomas Hertel, expanded the original GTAP global CGE model to include a land allocation module, primarily for the purpose of studying the effects of biofuel production (Hertel et al., 2009a). The Emissions Prediction and Policy Analysis Model (EPPA), developed by researchers at the Massachusetts Institute of Technology, is the second widely-used CGE model with an integrated land allocation module used for bioenergy impact assessment (Paltsev et al., 2005). These two models are highlighted due to their unique and novel approaches to modelling land allocation in a general equilibrium framework, as well as their influential studies exploring the potential impacts of bioenergy production on global land allocation.

Land-use change analysis in the GTAP model uses a nested constant elasticity of transformation (CET) function land substitution approach. The CET frontier specification was originally introduced by Powell and Gruen (1968) and is analogous to the well-known constant elasticity of substitution functional form.[5] An initial endowment of land resources is allocated to households who then allocate this land to firms for productive uses. Acknowledging that land as a factor of production is very different than labor and capital, optimal allocations to firms involves a sluggish transformation process if land is reallocated from one use to another. GTAP captures this sluggishness by imposing elasticity of transformation constraints on land allocation using the nested CET approach. While several nesting structures have been specific in GTAP land-use change analyses, panel (a) in Figure 2.5 shows a recent application (Taheripour et al., 2011b). At the top level, total land cover is allocated to either forest, pasture, or cropland. Cropland is then allocated to either conventional agricultural commodities or enrolled in the Conservation Reserve

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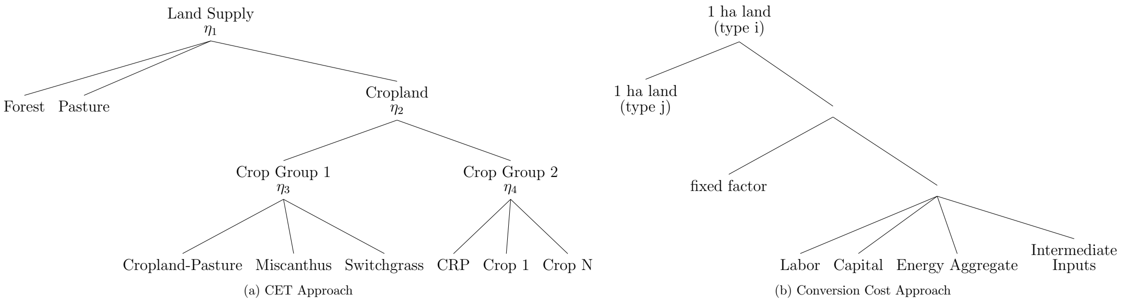
[5] A simple, single nest CET function takes the form $Y = \left( \sum_i \alpha_i x_i^{1+\frac{1}{\eta}} \right)^{\frac{1}{1+\frac{1}{\eta}}}$, where $Y$ is transformed into $x_i$, $i = 1...n$, with respective shares $\alpha_i$. $\eta$ is the elasticity of transformation.



(a) CET Approach

(b) Conversion Cost Approach

Figure 2.5: Examples of General Equilibrium Land Allocation Methods

Program (crop group 2) or allocated to advanced bioenergy feedstock uses, such as perennial grass production (crop group 1). Each of these decision points in the nest is governed by an elasticity of transformation, $\eta_{1,2,3,4}$. The transformation elasticities govern the flexibility by which land can be converted from one use to another in response to a policy shock in the model. A nesting structure allows for various assumptions to be made about the elasticity of transformation between different land types and uses. For example, we would expect elasticities in the top nest to be relatively inelastic due the high conversion costs, regulatory constraints, and other factors associated with broad land class transformation. However, crop 2 nest elasticities should be more elastic as producers can alter crop choices on existing cropland relatively easily. Very little is known about transformation elasticities for cellulosic feedstocks, such as switchgrass, since there is little observable data. Also, note that a land supply elasticity (for a given land class, lc), $\epsilon^s_{\text{lc}}$, can be derived from the transformation elasticity according to $\epsilon^s_{\text{lc}} = \eta(1 - \alpha_{\text{lc}})$, where $\alpha_{\text{lc}}$ is the share of a given land class in the appropriate nest (Hyman et al., 2003). The CET approach is used in this dissertation and described in greater detail in Chapter 3.

The EPPA model takes a very different approach when modelling land-use change, shown in panel (b) of Figure 2.5. Instead of parameterizing land substitution functions, the model factors in a cost of converting land from one use to another.[6] In essence, land of one type is "produced" from land of another type. A transfer of land from one type to another is assumed to required additional costs, such as labor, energy, capital, and other intermediate inputs. A "fixed factor" is also specified to allow for some sluggishness in land conversion over time, due to policy constraints on the maximum allowable land conversion in a region over a given period. If land is to be converted from one use to another, the differential in profit margins between the existing and proposed use must be greater than the one-time cost of converting that land. The conversion cost methodology is applied only to broad land class transitions, such as forest-to-cropland, forest-to-pastureland, pastureland-to-cropland, etc. Gurgel et al. (2007) compares the EPPA and CET land allocation approaches and finds that the GTAP method is more suited to short/medium-run analysis, whereas the EPPA approach better captures long-run economic pressures to reallocate land.

With an understanding of these two general land allocation methodologies, the following sections will review the results of studies exploring the land-use change effects of various biofuel expansion scenarios.

#### 2.3.1.1 GTAP Land-Use Results

Keeney and Hertel (2009) is arguably the seminal economics paper on biofuel-induced land-use change. Using the GTAP model described above the authors simulate the effects of a one billion gallon increase in U.S. ethanol demand, focusing on the land reallocation effects across agricultural sectors and broad land use categories. In general they find that land allocated to crops in the United States increases by 0.1%, with reductions in forest and

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[6] This approach was originally described in the EPPA model documentation before being applied in model policy analysis (Paltsev et al., 2005).

pastureland of 0.035% and 0.53% respectively. Within the agricultural sector they find that land allocated to coarse grains increases by 1.66%, while land allocated to oilseeds and other grains decreases by 1.14% and 1.31% respectively. These are fairly dramatic changes given that the authors are only considering a one billion gallon consumption mandate. Assuming that the opportunity cost of land increases at an increasing rate, we would expect non-linear land-use affects as higher biofuel volumes are produced. International land-use effects are also reported, with the largest changes appearing in Canada, Brazil, and the European Union. A general pattern emerges whereby other regions of the world increase crop production as U.S. agricultural commodity exports decline. New agricultural land tends to be evenly drawn from both forest and pastureland in most regions.

A key insight of Keeney and Hertel (2009) is that results are sensitive to both acreage-response and yield-response to changes in crop price. The acreage effect dictates the ability to substitute land between broad land classes in response to changes in relative agricultural commodity prices. This is captured by the CET parameter in the top nest in the structure described above. The yield effect acknowledges that as agricultural commodity prices increase, incentives are created to increase yields on existing land (primarily through increased fertilizer application). This yield response is a novel contribution from the GTAP group and could potentially be an important parameter in future work on cellulosic feedstocks, although currently, very little is known about the yield response for these advanced bioenergy feedstocks. In fact, very little is known in general about agricultural yield-price responses, except that they are most likely non-negative.

Whereas the Keeney and Hertel (2009) study was concerned primarily with the marginal land use effects of the U.S. biofuel mandate, Hertel et al. (2010) report the effects of fully implementing the conventional ethanol component (corn ethanol) of the U.S. Renewable Fuel Standard. They find that global cropland increases by 3.8 million hectares (an indirect land use effect), with the majority of new land coming from pastureland. In contrast to Keeney and Hertel (2009), only a small fraction comes from cleared forests. As an aside, these forest-to-cropland conversions drive the terrestrial greenhouse gas burden associated with the iLUC effect. The majority of the forest-clearing is projected to occur in the United States, Canada, and Europe. Non-trivial land conversion also occurs in Latin America and Africa, although the study suggests that much of this is from pastureland to cropland, which has a lower greenhouse gas footprint.

In a GTAP working paper, Tyner et al. (2010) provide a comprehensive overview of the study results reported above. These findings are used to project greenhouse gas emissions factors due to iLUC for the California Low Carbon Fuel Standard (LCFS). Wang et al. (2011) further summarize these finding and note that current model predictions of land-use change tend to be less than half as large as those reported in original land-use change studies (e.g. Searchinger et al., 2008) and slightly lower than estimates used by the Environmental Protection Agency and the California Air Resources Board in their iLUC factor calculations.

Very preliminary results have been reported for the land-use change effect of several cellulosic feedstocks in Taheripour et al. (2011a). They find that 0.15-0.16 hectares of new land is needed for every 1,000 gallons of advanced biofuel produced from switchgrass. This is only slightly below that needed for corn ethanol production (0.18).[7] The land requirement for miscanthus is approximately half of that for switchgrass, due to higher yields. In general

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[7] Original projections in Tyner et al. (2010) suggest that 0.12 hectares of land are needed per 1,000 gallons of corn ethanol produced, which suggests that cellulosic biofuel production from switchgrass is less efficient than corn. These results are more consistent with the findings presented in Chapter 4.

they find that the vast majority of new land is converted from pastureland (although this result appears to be driven largely by modelling assumptions). The authors do not report the land-use effects of cellulosic feedstock production on existing agricultural commodity acreage, ie, changes at the intensive land margin.

#### 2.3.1.2 EPPA Land-Use Results

The MIT EPPA modelling group takes a different approach to modelling global bioenergy expansion, not just in how land allocation is modelled, but also with respect to the policy scenarios that drive bioenergy production. Instead of implementing bioenergy production/consumption mandates, EPPA uses GHG emissions constraints to drive low GHG emissions technologies, such as biofuel.

Interestingly, Gurgel et al. (2007) find that under a global carbon abatement policy, bioenergy production in the United States plays a very minimal role in reducing emissions. The majority of bioenergy is produced in Latin America and Central Africa, due primarily to highly productive land in these regions that is available at low cost. Of course, the policy instrument chosen only takes into account the efficient allocation of bioenergy production under a GHG policy, and does not consider many other domestic objectives, such an energy security and rural development, that are also important in determining national bioenergy policies. Using the conversion cost methodology described above, the EPPA model finds that much of the new land for bioenergy feedstock production comes from natural forests. The study compares these results to an identical biofuel expansion scenario using the GTAP land allocation methodology, and find that under the CET approach the majority of new land for bioenergy production comes from pastureland. This difference suggests that land conversion assumptions play a pivotal role in understanding what type of ecosystems will be converted to make way for bioenergy production. In the short to medium-run, we would expect to see cropland exerting pressure on pasturelands; however, as food, feed, and fuel demands continue to rise, the added demand for land from the fuel sector will put additional pressure on forest resources. As a final note, the study also suggests that cropland used for conventional food/feed purposes does not change much as bioenergy expands, suggesting that aggressive bioenergy programs will not crowd out conventional agricultural commodities, due to the inelastic demand for food. The primary impact will be on native forest and grasslands.

Melillo et al. (2009) extends these findings to explore the greenhouse gas implications of bioenergy-induced land use change. Not suprisingly, they find that under the conversion cost methodology, whereby large tracts of forest are converted to bioenergy production, the greenhouse gas footprint is considerably negative. Note that under this scenario, terrestrial emissions are not subject to the GHG emissions regulations that drive technological change in the energy sectors. If such emissions were subject to the policy we would expect much less bioenergy production. In fact, they find that aggressive bioenergy expansion results in a higher level of total GHG emissions than if not used at all. If the alternative land conversion methodology is specified and large tracts of pastureland are used for bioenergy production, the biofuel expansion results in a net GHG reduction. In both cases, emissions associated with land-use change significantly lowers the potential for bioenergy to reduce GHG emissions.

#### 2.3.1.3 Other CGE Land-Use Results

Several other studies have used general equilibrium models to estimate land-use change from biofuel production. Using a modelling framework very similar to GTAP, Timilsina et al. (2010) simulate a global bioenergy expansion, significantly larger than any of those in the GTAP studies. The authors assume that all proposed national bioenergy targets are met in 2020 (excluding all cellulosic biofuel mandates), increasing global biofuel production between 64.5% and 153.2% beyond 2009 levels. Forest clearing and pastureland conversion to cropland occurs at a much higher level than in the GTAP or EPPA studies cited above. In fact, the authors predict over 18 million hectares of forest clearing (primarily in Brazil and Canada). While the model includes many of the advanced features of the GTAP model, such as DDGS crediting and yield/acreage responses, the large differences in acreage conversion to cropland is likely due to two factors. First, the larger bioenergy expansion scenario, and second, considerably more elastic land transformation elasticity assumptions. The latter illustrates the sensitivity of this class of model to land supply assumptions.

Finally, van Meijl et al. (2006) and Eickhout et al. (2009) integrate a modified GTAP model (LEITAP) with the Integrated Model to Assess the Global Environment (IMAGE), a detailed global land use model developed by researchers at the Netherlands Environmental Assessment Agency. The land allocation mechanism in LEITAP is very similar to the GTAP nesting structure described in panel (a) of Figure 2.5. A key contribution is the use of the biophysical model, IMAGE, to determined land supply elasticities used in the economic model, LEITAP. IMAGE can estimate the relationship between yield and total acreage at a much finer scale than any of the land-use data used in the economic models described above. Fitting a functional form to the relationship of inverse yield and total acreage provides a physical analogue to an economic land supply curve. The authors then assume that inverse yield is a proxy for the marginal productivity of a given area of land, and estimate the elasticity of this relationship. This elasticity is then used in LEITAP for the land supply function. The output from the economic model is also used in IMAGE to estimate environmental impacts from the economic/policy scenarios.

While there do not appear to be any published studies explicitly analyzing the land-use effects of bioenergy production using the LEITAP/IMAGE framework, this approach is discussed here as an example of the research frontier for global land-use change research, where economic and biophysical models are fully integrated. Because simulation results are highly sensitive to land supply and conversion elasticities, it makes sense to take advantage of the greater spatial variability of land provided in biophysical models such as IMAGE.

#### 2.3.1.4 Partial Equilibrium Results

Partial equilibrium models have also been widely used in the economics literature to address the issue of bioenergy-induced land-use change. For example, in determining the greenhouse gas emissions associated with iLUC, the U.S. Environmental Protection Agency relied on results from the FAPRI/CARD partial equilibrium model (discussed above). These results were then used to develop regulatory guidelines for determining the lifecycle GHG footprint of various biofuel pathways. An important advantage of these models is their ability to include more detailed land cover data for particular regions of interest, which is often not available in a general equilibrium framework that requires uniform accounting practices across all regions and sectors. This section will briefly summarize the findings in these studies.

Searchinger et al. (2008) was largely responsible for highlighting the terrestrial GHG implications associated with market-induced land-use changes due to biofuel production. The land conversion results (reported in the article's supplementary material) showed extremely large quantities of tropical forests being converted to crop production in South/Southeast

Asia, Latin American, and Africa, largely to in response to higher agricultural commodity prices resulting from a decrease in U.S. exports. Only in the United States (the second largest source of terrestrial ecosystem GHG emissions) was land expected to be drawn from grasslands into agricultural production at a large scale. Using the FAPRI/CARD model, the authors find that GHG emissions from corn ethanol production were 93% higher than the gasoline baseline, of which nearly 60% was due to iLUC-induced terrestrial emissions. Advanced biofuels (using non-corn feedstocks) performed only slightly better, increasing emissions 50% above the gasoline baseline, and of which 80% was due to iLUC-induced emissions.

Using the same partial equilibrium model and data as Searchinger et al. (2008), Dumortier et al. (2011) updated a number of assumptions and found that the iLUC effects from corn ethanol production were dramatically lower than reported in the original study. Including a yield-crop price relationship, similar to that proposed by Keeney and Hertel (2009), reduced iLUC-induced emissions by over 85%. The study also found that original estimates of idled cropland in the U.S. were most likely too low. Including this idled agricultural land decreases the burden on the rest of the agricultural production system. Fabiosa et al. (2010a) applies the FAPRI/CARD model to both a U.S. and global ethanol expansion scenario and reports land-use impact multipliers. Total additional crop acreage due to a U.S. biofuel expansion is projected to be approximately 60-65% lower than the original Searchinger et al. (2008) projections. The authors suggest that the primary difference between the results is the assumption in Searchinger et al. (2008) that the biofuel industry continues to expand until all economic profits are exhausted. In reality, as discussed in

Section 2.1.1, new investment in ethanol refineries tends to slow well before processing margins converge to zero.

Havlik et al. (2011) use the Global Biomass Optimization Model (GLOBIOM), developed at the International Institute for Applied Systems Analysis (IIASA), to analyze the land-use change implications of a both conventional and advanced biofuel production. An important contribution of this work is the development of an alternative global land cover data set, based on more detailed land productivity and climate estimates. They report land-use change and associated terrestrial GHG emissions on a scale similar to the studies cited above, but show that second-generation feedstocks could considerably reduce the iLUC effects. However, this result in based on an *assumption* that cellulosic feedstocks are grown on land that is not competitive with conventional crop production. Relaxing this assumption, the authors find that the iLUC effect for cellulosic feedstocks can actually be worse than efficient first-generation biofuel processes.

Chen et al. (2011) develop the Biofuel and Environmental Policy Analysis Model, BEPAM, a partial equilibrium model of the U.S. agriculture and fuel sectors. BEPAM utilizes land cover data from USDA's National Agricultural Statistics Service (NASS), which provides much more detailed land information than the global models described above, although at the expense of being capable of predicting international land-use conversion patterns. Acreage response functions are calibrated based on historically observable changes in domestic land-use patterns (described in Huang and Khanna, 2010, below). BEPAM is also able to predict domestic land reallocation as a result of cellulosic bioenergy production. Results show that implementing the full Renewable Fuel Standard increases total land for crop and bioenergy production by 5% in 2022. 7.46 million hectares is used for dedicated energy crops (switchgrass and miscanthus), 95% of which comes from idled cropland and pastureland. Total corn acreage also increases by 13%, whereas land used for wheat and soybean production declines 3% and 8%, respectively. One important assumption of the study is that forest clearing is not allowed for cropland expansion. While perhaps justifiable under a short time horizon, the general equilibrium results above such that forest conversion to pastureland or cropland could very well occur if the U.S. biofuel targets are met.

Directly comparing land-use change results of partial equilibrium models to general equilibrium models is a difficult task. Results appear to be highly sensitive to land allocation methodologies, implied land supply elasticities, yield responses to changes in crop price, assumptions regarding the availability of idled agricultural land, and other behavioral relationships. Despite these difficulties, the literature has been directionally consistent in predictions of land-use change, although the magnitude of such changes appears to have originally been overstated. Considerable uncertainty remains as to the true magnitude of the land-use change effects and more importantly, the implications for terrestrial GHG emissions.

Two regulatory regimes exist in the U.S. that require a measurement of direct and indirect LUC-induced GHG emissions: the U.S. Renewable Fuel Standard and the California Low Carbon Fuel Standard (LCFS). It is largely due to the financial consequences to biofuel producers looking to qualify in these two programs that the iLUC debate has become a top research priority. Recent critiques have suggested that iLUC-induced GHG emissions should be excluded from biofuel regulations. Zilberman et al. (2011) and Zilberman et al. (2010) argue that imposing the iLUC standard on biofuel producers has several adverse affects. First, because land-use change is a second-order effect that is not controlled directly by biofuel producers, regulating associated emissions does not provide direct incentives for producers to change their behavior and become more efficient. The authors argue that this ultimately slows the rate of technological innovation in the biofuels sector, perhaps inhibiting the production of lower emissions biofuel pathways. Second, the iLUC effect is only one market-mediated response that effects the greenhouse gas footprint of biofuel production. Excluding other indirect effects, such as iFUC (described above), creates a regulatory inconsistency which may be legally indefensible. Furthermore, this second-best approach may reduce the political feasibility of finding more efficient policy solutions to GHG emissions. Babcock (2009) argues that such complex global land-use models have traditionally been used to highlight tradeoffs for policy-makers to consider, not to be used in a regulatory context. Because the models are now used to make *ex ante* predictions, often for policies that have never before been implemented, the results cannot be truly validated, as economic conditions will inevitably deviate from the modeler's assumptions. This does not imply that the predictions are not "true," but without the ability to validate, the exact magnitude of any predicted effect can be challenged. Regulating indirect impacts should therefore be viewed as a second-best environmental policy. While unregulated GHG emissions from terrestrial ecosystem conversion is certainly a market failure, a more efficient method of regulation is to implement a global GHG-pricing scheme.

### 2.3.2 Land Supply Elasticity Estimates

As should be apparent in the land-use results from the structural models described above, correctly parameterizing the land supply functions in the domestic and global agricultural complex is an important area of research. These parameters are a driving factor in determining the magnitude of biofuel expansion impacts not only on agricultural markets, but on environmental services as well. A small body of literature has developed in the past several years that attempts to estimate these parameters at a scale suitable for national or global impact assessment analysis.

Huang and Khanna (2010) estimate both the acreage-price elasticity and yield-price elasticity for major crops in the United States. They find that the acreage/own price elasticities for corn and soybeans are nearly identical, at approximately 0.5. Wheat showed a much more inelastic acreage response over the study period, at approximately .067. A composite acreage elasticity, factoring in price and acreage changes for all major crops, was 0.257. Yield elasticities (with respect to own-price changes) were 0.15, 0.43, and 0.06 for corn, wheat, and soybeans, respectively.

Swinton et al. (2011) conducted a similar exercise using data from 2007-2009 and argue that there is only limited available marginal land in the U.S., based on the land supply response by producers of major crops to the large price and profitability increases experienced over this period. The authors report an acreage/price elasticity of 0.032 for major crops, which is considerable lower than the estimate reported in Huang and Khanna (2010). One might expect that the acreage elasticity for dedicated energy crops, such as perennial grasses, is likely to be even lower because of the higher economic risk and lack of fully developed bioenergy feedstock markets. On the other hand, these elasticities were measured, in both studies, over a fairly short period of time. Medium/long run acreage elasticities could be considerably more elastic. This issue presents a challenge for modelers using structural simulation methods regarding the appropriate elasticity to use and interpreting the results over a suitable time horizon. It is also important to note that these studies, while important for biofuel analysis, are not explicitly measuring acreage and yield elasticities for cellulosic feedstocks. This will be a very important area of future research as the industry expands.

Using a logit model of land-use choice, Langpap and Wu (2010) find that a 1% increase in corn price increases the probability of allocating a parcel of land to crop production by 0.06% and 0.14% in the Corn Belt and Great Lakes regions, respectively. In the Corn Belt, a similar acreage response is found for changes wheat and hay price. The acreage response to wheat price in the Great Lakes region is actually estimated to be negative (suggesting an increase in wheat price decreases the likelihood that a parcel of land will be allocated to crop production). While these elasticity estimates are not directly substitutable into the structural modelling frameworks described above, they do partially validate the relatively inelastic acreage response assumptions into those models. However, the two-fold difference between acreage responses in the Corn Belt and Great Lakes highlights the potential variability in regional estimates, which is important because global general equilibrium models must choose a single elasticity assumption for the U.S.

### 2.3.3 Regional Feasibility of Cellulosic Feedstock Production

The ability to meet to the cellulosic biofuel mandate in the Renewable Fuel Standard, and the potential economic impacts of doing so, will depend largely on where cellulosic biomass is sourced from, and at what cost. While Chapters 3 and4 discuss the specific input costs required to produce various feedstocks, this section will describe the results from several studies on the regional variability and viability of cellulosic feedstock production.

Perlack et al. (2005) was a seminal study on the technical feasibility of producing biomass for energy in the United States. The study, often referred to as "The Billion-Ton Study," was recently updated to consider both the technical and economic feasibility of biomass production (Perlack and Stokes, 2011). Using the POLYSYS partial equilibrium model, the study estimates national supply curves for forest biomass, agricultural residues, and dedicated energy crops such as perennial grasses and short-rotation woody crops (De La Torre Ugarte and Ray, 2000). In general the Billion-Ton Study predicts several important trends. First, at low biomass prices ($40/dry ton), agricultural residues are likely to be the predominant cellulosic feedstock, with dedicated energy crops becoming increasingly viable in the $50-$60/ton range. At $60/ton, perennial grasses are expected to occupy 43 million acres (17.4 million hectares) by 2030. Second, agricultural residue production is expected to be highest in the Corn Belt, while dedicated energy crops are expected to dominate in the Central/Southern Plains region and southeast United States.

Khanna et al. (2011) apply BEPAM (described above) and conduct an identical exercise as Perlack and Stokes (2011). While the geographic distribution results are generally similar, several interesting critiques were made in reference to the Billion-Ton Study. First, the authors find that biomass prices well in excess of $60/ton (the upper-bound price in the Billion-Ton Study) are required to bring more than 500 million metric tons of total biomass in production. In fact, much of the national biomass supply curve is in the $60-$120/ton range. Second, the authors find that the agricultural residue supply curves become virtually perfectly-inelastic after 75 million acres of corn stover and 50 million acres of wheat straw is harvested. Perennial grasses, especially miscanthus, become essential for acquiring cellulosic biomass once the residue market has been saturated.

It is important to consider these results carefully when analyzing the global implications of a U.S. cellulosic bioenergy expansion. Distortions in conventional agricultural commodity markets will depend in large part on what type of cellulosic feedstocks are grown and in which regions.

## 2.4 Conclusion

The two unintended consequences of biofuel production (and policy) most studied in the literature thus far have been the food/fuel tradeoff and the impact of land-use change on terrestrial GHG emissions. Often it is assumed that minimizing the costs associated with both of these effects is a worthwhile policy objective; however, the literature review conducted here provides a valuable insight. There is a **tradeoff** between food security (ie, commodity price volatility) and terrestrial GHG reductions. Holding technological change constant, meeting food security objectives requires easing agricultural production constraints, primarily by increasing the agricultural land base. However, increasing this land base is the exact driver of terrestrial GHG emissions. Quantifying this tradeoff is an important area of future inquiry.

While the existing biofuel economic impact is quite extensive, focusing primarily on the effects of conventional biofuel production, nearly all studies rely on a single economic concept: Biofuel production induces second-order effects through market-mediated responses. This concept has been shown in agricultural commodity and livestock markets, domestic and international transportation fuel markets, and greenhouse gas mitigation strategies. Because biofuel production and consumption links an array of complex global markets, the need for such analysis is extensive. It can be anticipated that such research will continue in order to provide more accurate estimates of currently recognized impacts, as well as shed light on new effects. One such area for future research is the effect of biofuel production on non-GHG ecosystem services. For example, introducing new cellulosic feedstocks is likely to alter the agricultural landscape in mixed-use ecosystems, such as in the Northern Plains region and Southeast U.S. Case studies have appeared, primarily in the ecology literature, in the case of biodiversity (Bellamy et al., 2009; Eggers et al., 2009), water quality (Thomas et al., 2009), and crop pollination (Gardiner et al., 2010), to cite just a few. Integrating these tradeoffs in economic policy models will help evaluate the comprehensive value of biofuel production, with the goal of responsibly informing the future path of biofuel production.

One additional gap in the existing literature is the commodity market and land-use impacts of biofuel production using cellulosic feedstocks. With U.S. mandates requiring the production of such fuels in high volumes over the next 5-10 years, understanding these impacts is a highly relevant area of inquiry. The remainder of this dissertation is dedicated to understanding these issues.

# Chapter 3

# Methodology

## 3.1 Introduction

In order to understand the economic impacts of bioenergy production and policy tradeoffs, the research in this dissertation draws heavily on structural economic modeling techniques. More, specifically, I use an Applied (or Computable) General Equilibrium (AGE or CGE) model of the global economic system. AGE models are a widely used tool for economic policy assessment. Such models are effective in capturing economy-wide interactions resulting from structural changes in a given economic sector, or set of sectors. While partial equilibrium models are an effective tool for analyzing a limited set of market interactions, large economic changes are better suited to a general equilibrium framework that captures the numerous comprehensive behavioral responses resulting in economy-wide resource allocation.

Certain research questions on energy and agricultural policy are well-suited to a global general equilibrium framework due to the linkages between numerous agents and markets. Bioenergy production, in particular, bridges these two economic sectors. Furthermore, the integration of global agricultural markets connects decisions made by agricultural producers in one country to consumer and producer decisions around the world, necessitating a tool that is able to capture these relationships. For these reasons, a general equilibrium modeling approach is utilized.

The general equilibrium framework described in this chapter builds on the class of models detailed in Arrow and Hahn (1971), known as the Arrow-Debreu general equilibrium framework. This model describes a closed economic system consisting of producers and consumers. Consumers own an initial endowment of the factors of production and demand commodities produced in the economy. Consumer preferences for commodities are assumed be convex, continuous, and non-satiated. Consumer demand functions are continuously differentiable, homogeneous of degree zero in prices, and satisfy Walras law (which requires that in equilibrium, consumption exhausts all income). Producers provide the economic system with commodities according to a constant returns to scale production function and allocate resources in order to maximize profits.

In a competitive market system, this general set of assumptions results in an efficient allocation of resources (commodities and factors) and prices, defined as a Walrasian equilibrium. The assumptions above also imply that producers earn zero economic profit in equilibrium (as a result of the constant returns to scale assumption), and that equilibrium price levels are relative, not absolute. The latter feature is a result of the assumptions that demand functions are homogeneous of degree zero in prices and producer profits are homogeneous of degree one in prices.

Using the same behavioral assumptions described above, an alternative, and very useful way to describe a Walrasian equilibrium, is by describing three accounting identities that must be satisfied: Market Clearance, Zero Profit, and Income Balance. Market clearance requires that in all commodity and factor markets, supply equals demand. The zero-profit condition states that the value of a commodity must be equal the sum of all input values (implying constant returns to scale for producers). Finally, income balance requires that all income accruing to households is subsequently spent on goods and services (or allocated towards savings) in the economy. The allocation of resources which satisfies these three conditions is the Walrasian equilibrium. In order to standardize the units in a general equilibrium model, relative prices for each commodity and factor are introduced. These prices are all relative to a numeraire good. The Walrasian equilibrium uniquely determines prices, income, and activity levels in the general equilibrium model, which is formulated as a mixed-complementarity problem.

This relatively straightforward description of a general equilibrium model is complicated by the number of economic agents, markets, structural equation nesting structures, and numerous other factors. However, the above principles are what defines this type of model, not the complexity introduced in section 3.4. A detailed, yet accessible, exposition of the applied general equilibrium framework is described in Wing (2004).

Due to advances in computational power, general equilibrium models have become an important tool in applied policy analysis. In the fields of agricultural and energy policy analysis, such models have gained wide popularity and are commonly applied to a variety of research topics (see Bhattacharyya, 1996; Tongeren et al., 2001; Kretschmer and Peterson, 2010, for relevant review articles). The methodology outlined below is in the tradition of this well-established economic policy assessment framework.

This chapter is organized as follows. Sections 3.2 and 3.4 describe the benchmark data set and structural equations of the Future Agricultural Resources Model (FARM), which is the particular general equilibrium model used in this dissertation. Section 3.3 describes the method for expanding the original data set and incorporating new economic sectors used in the bioenergy module.

FARM was developed in 2010 by researchers at the USDA Economic Research Service (ERS) in order to answer a wide range of questions about the policy impacts of various agricultural and energy policies.[8] The model uses the GTAPinGAMS modeling platform as a point of departure, which is itself based on widely used global trade model developed at at Purdue University (Rutherford, 2005; Hertel, 1998).

## 3.2 GTAP Benchmark Data

FARM uses the data set compiled by the Global Trade Analysis Project (GTAP), describing production, consumption, and bilateral trade relationships for the global economy (Narayanan and Walmsley, 2008). Since it was first introduced in 1993, the GTAP data base has undergone six revisions, with periodic updates made in order to capture a snapshot of global economy for a given period of time. The most recent version, GTAP 7, is used in this dissertation and reflects the 2004 global economy. This section describes the primary data arrays and accounting identities in the benchmark data that describes the flow of goods, services, and factors of production that are used to calibrate FARM for policy analysis.

The GTAP 7 data covers 113 regions ($r$), 57 economic sectors ($a$) and commodities ($c$), and 5 primary factors of production ($b$). Three of these factors- skilled labor, unskilled labor, and capital- are defined as *mobile* ($mf \subset b$), in the sense that the net marginal return is identical across all sectors. Two of these factors- land and natural resources- are *sluggish* ($sf \subset b$), meaning that factor returns are sector specific. These factors are discussed in more detail below. The notation used here follows the GTAP notation closely (see Hertel (1998)) but has been adapted by Rutherford (2005). All economic values in the benchmark data are in billions of 2004$ U.S. Portraying the data in economy values (price x quantity) allows for standardization across all economic sectors and therefore allows for a unified accounting

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[8] An earlier version of FARM was developed in the 1990's by economist Roy Darwin for economy-wide energy and agriculture analysis. However, aside from the name and the application to global energy and agriculture issues, the 2010 version of FARM has very little resemblance to this earlier version.

framework. Base year flows described in this section are all exogenous model parameters, and following standard convention are denoted in lower-case, while the endogenous model variables, described in 3.4, are denoted in upper-case.

In the commodity markets, total supply ($vom_{a,r}$) consists of the value of all inputs used by sector $a$. This consists of primary factors ($vfm_{b,a,r}$), intermediate input demand for domestic commodities ($vdfm_{c,a,r}$), and intermediate demand for commodities produced in other countries ($vifm_{c,a,r}$). Final demand for domestic supply is distributed between domestic household consumption ($vdpm_{c,r}$), domestic government consumption ($vdgm_{c,r}$), intermediate firm demand ($vdfm_{c,a,r}$), exports ($vxmd_{c,r,s}$), investment demand ($vdim_{c,r}$), and international transportation services ($vst_{c,r}$).[9]

In addition to private (firm and household) and public sector demand for domestic goods ($vdpm_{c,r}$,$vdgm_{c,r}$,$\sum_c vdfm_{c,a,r}$), aggregate demand ($vdm_{c,r}$) in region $r$ also consists of total domestic demand for imported goods ($vim_{c,r}$) by households ($vipm_{c,r}$), government ($vigm_{c,r}$), and firms ($\sum_c vifm_{c,r}$). For simplicity, aggregate public demand and aggregate private demand are denoted as $vgm_{c,r}$ and $vpm_{c,r}$, respectively.

Household income is derived from primary factor payments ($vfm_{b,a,r}$), while government income is derived from tax revenue. There are ten types of tax rates calculated from the GTAP data set: output subsidy rates ($\bar{t}^{y}_{c,r}$), taxation of household's income derived from primary factors ($\bar{t}^{HH}_{b,a,r}$), private domestic and import consumption taxes, ($\bar{t}^{P^d}_{c,r}$ and $\bar{t}^{P^m}_{c,r}$), government domestic and import consumption taxes ($\bar{t}^{G^d}_{c,r}$ and $\bar{t}^{G^m}_{c,r}$), firms' domestic and

---

[9] While investment demand, $vdim_{c,r}$, is indexed by the commodity set $c$, it is comprised of only a single investment "commodity." This is a modeling convention in GTAP to allow for allocation of resources towards savings in a static model. The reader should remember that $vdim_{c,r}$ is simply a 1 x $r$ vector.

import consumption taxes ($\bar{t}^{F^d}_{c,a,r}$and $\bar{t}^{F^m}_{c,a,r}$), export subsidy rates ($\bar{t}^{X}_{c,r,s}$), and import tax rates ($\bar{t}^{M}_{c,r,s}$).

Tax rates for output, primary factors, and domestic/foreign commodity consumption (firm, household, and government) are calculated as the ratio of expenditures at "agent" prices to expenditures at "market" prices. For import/export taxes, rates are calculated as the ratio of "world" prices to domestic market prices. Expenditures at agent prices are measured in the GTAP data base using the observable price individual economic agents actually pay for a good, service, or factor, whereas expenditures market prices are measured using the price that optimizing agents should theoretically pay in market equilibrium. The difference between these two expenditures must therefore equal the ad valorem tax paid by an economic agent. Because tax rates are explicitly calculated based on the benchmark data and incorporated as such into the modeling framework, data arrays of expenditures at agent prices are not used in FARM except to calculate these initial tax rates. This ad valorem tax rate calculation, based on Rutherford (2005) differs from the GTAP tax calculation. The GTAP model is linearized and therefore tax rates should be interpreted as the 'power of the tax,' not an ad valorem tax. The 'power of the tax' is simply the ratio of expenditures at agent prices to expenditures at market prices. The ad valorem representation is one minus this ratio. Total tax revenue and subsidy payments is defined as

$$\bar{\Re}_r = \bar{\Re}^o_r + \bar{\Re}^{HH}_r + \bar{\Re}^{F^d}_r + \bar{\Re}^{F^i}_r + \bar{\Re}^{P^d}_r + \bar{\Re}^{P^i}_r + \bar{\Re}^{G^d}_r + \bar{\Re}^{G^i}_r + \bar{\Re}^{x}_r + \bar{\Re}^{m}_r$$

Where domestic output and primary factor tax receipts are:

$$\bar{\Re}^y_r = \sum_a \bar{t}^y_{a,r} * vom_{a,r} \qquad \bar{\Re}^{HH}_r = \sum_{b,a} \bar{t}^{HH}_{b,a,r} * vfm_{b,a,r}$$

Firm, household, and government consumption tax receipts from domestic and international purchases are:

$$\bar{\Re}_r^{F^d} = \sum_{c,a} \bar{t}^{F^d}_{c,a,r} * vdfm_{c,a,r} \qquad \bar{\Re}_r^{F^i} = \sum_{c,a} \bar{t}^{F^m}_{c,a,r} * vifm_{c,a,r}$$

$$\bar{\Re}_r^{P^d} = \sum_{c} \bar{t}^{P^d}_{c,r} * vdpm_{c,r} \qquad \bar{\Re}_r^{P^i} = \sum_{c} \bar{t}^{P^m}_{c,r} * vipm_{c,r}$$

$$\bar{\Re}_r^{G^d} = \sum_{c} \bar{t}^{G^d}_{c,r} * vdgm_{c,r} \qquad \bar{\Re}_r^{G^i} = \sum_{c} \bar{t}^{G^m}_{c,r} * vigm_{c,r}$$

and export subsidy expenditures and import tariff revenues are:

$$\bar{\Re}_r^{x} = \sum_{c,s} \bar{t}^{X}_{c,r,s} * vxmd_{c,r,s} \qquad \bar{\Re}_r^{m} = \sum_{c,s} \bar{t}^{M}_{c,s,r} \left( (1 - \bar{t}^{x}_{c,s,r}) vxmd_{c,s,r} + \sum_{a} vtwr_{c,a,s,r} \right)$$

Table 3.1 summarizes the definitions and identities set forth thus far. A visual representation of the base year value flows, adapted from Rutherford (2005), is shown in Figure 3.1.

In order to satisfy the Walrasian equilibrium requirements in part 3.1, all markets must clear, all economic sectors must earn zero economic profits, and the household and government budgets must be fully exhausted.

With supply on the left side of the equation and demand on the right, the market clearance conditions are defined as follows:

$$\text{Domestic Commodity Markets:} \quad \sum_{b} vfm_{b,a,r} + \sum_{c} vdfm_{c,a,r} + \sum_{c} vifm_{c,a,r} =$$
$$vdpm_{c,r} + vdgm_{c,r} + \sum_{a} vdfm_{c,a,r} + \sum_{s} vxmd_{c,r,s} + vdim_{c,r} + vst_{c,r}$$

$$\text{International Commodity Markets:} \quad vxm_{c,r} = \sum_{s} vxmd_{c,r,s}$$

$$\text{Factors Markets:} \quad \sum_{a} vfm_{b,a,r} = evom_{f,r}$$

$$\text{International Transportation Services:} \quad vt_a = \sum_{c,s,r} vtwr_{c,a,s,r}$$

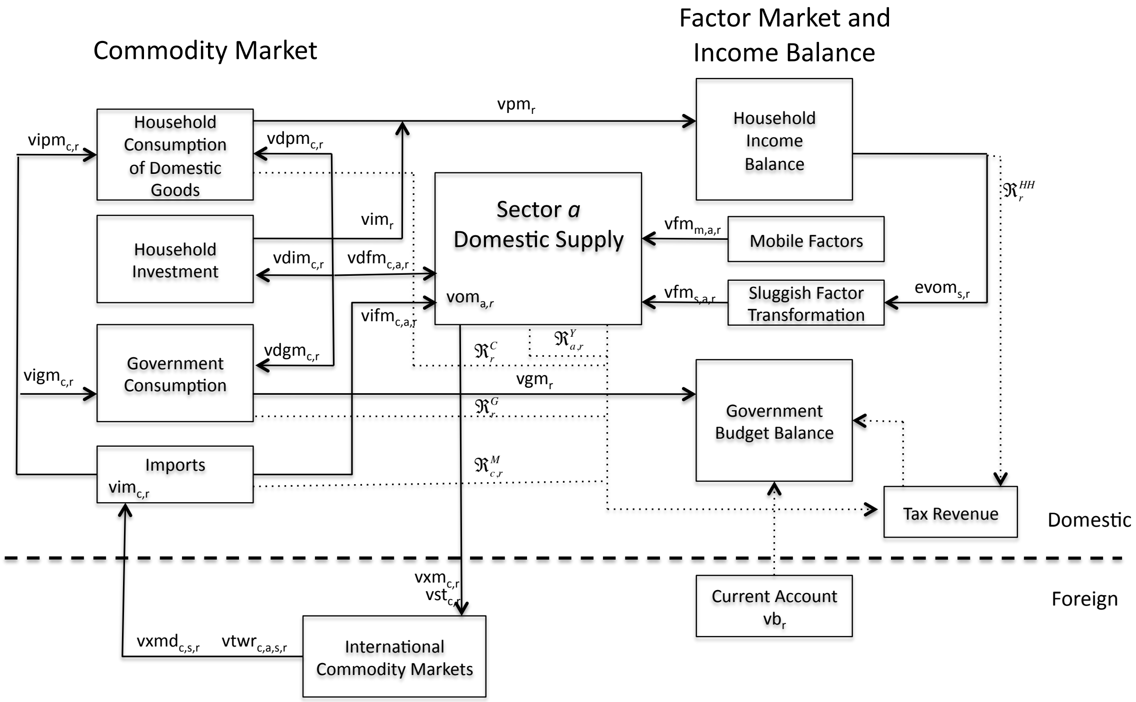

Figure 3.1: Value Flows in GTAP 7 (adapted from Rutherford (2005))

The zero-profit conditions required that the total value of output (LHS of the equation) in the commodity and factor markets equal the sum cost of all inputs (RHS of the equation).

Domestic Commodity Markets

$$vom_{a,r} = \sum_b vfm_{b,a,r} + \sum_c (vdfm_{c,a,r} + vifm_{c,a,r})$$

International Commodity Markets (Imports)

$$vim_{c,r} = \sum_s vxmd_{c,s,r} + \sum_{a,s} vtwr_{c,a,s,r}$$

Household Consumption

$$vpm_r = \sum_c (vdpm_{c,r} + vipm_{c,r}) + \bar{\Re}_r^{P^d} + \bar{\Re}_r^{P^i}$$

Household Investment

$$vim_r = \sum_c vdim_{c,r}$$

Table 3.1: Benchmark Data Arrays and Identities

| GTAP 7 Data Arrays | |
|---|---|
| $vdfm_{c,a,r}$ | Firm Intermediate Demand for Domestic Goods |
| $vdgm_{c,r}$ | Government Purchases of Domestic Goods at Market Prices |
| $vdpm_{c,r}$ | Private Households Purchases of Domestic Goods at Market Prices |
| $vifm_{c,a,r}$ | Firm Intermediate Demand for Imported Goods |
| $vigm_{c,r}$ | Government Imports at Market Prices |
| $vipm_{c,r}$ | Private Households Imports at Market Prices |
| $vfm_{b,a,r}$ | Firm Demand for Primary Factors |
| $vxmd_{c,r,s}$ | Bilateral Exports at Market Prices |
| $vtwr_{c,cc,r,s}$ | Margins for International Transportation Services |
| $vst_{c,r}$ | Exports for International Transportation Services |
| $vdim_{c,r}$ | Investment Demand |

| GTAP 7 Identities | |
|---|---|
| $vom_{a,r}$ | Value of Domestic Supply |
| $vpm_r$ | Aggregrate Household Demand |
| $vgm_r$ | Aggregrate Government Demand |
| $vdm_r$ | Aggregrate Demand |
| $evom_{b,r}$ | Household Primary Factor Endowments |
| $vim_{c,r}$ | Aggregate Imports by Commodity |
| $vxm_{c,r}$ | Aggregate Exports by Commodity |
| $vt_c$ | Global Transportation Services Provided, by Commodity |
| $vb_r$ | Current Account Balance |

Government Consumption

$$vgm_r = \sum_c (vdgm_{c,r} + vigm_{c,r}) + \bar{\Re}_r^{G^d} + \bar{\Re}_r^{G^i}$$

Sluggish Factors

$$evom_{b,r} = \sum_a vfm_{b,a,r}$$

International Transportation Services

$$\sum_r vst_{a,r} = vt_a = \sum_{c,r,s} vtwr_{c,a,r,s}$$

The final set of general equilibrium conditions are the income balance constraints for regional households and governments. The household budget constraint says that total income derived from the primary factors (net of factor tax payments), must equal expenditures on goods and services or allocated towards saving.

$$\sum_b evom_{b,a,r} - \Re_r^{HH} = vpm_r + vim_r$$

The public sector budget constraint for governments requires that total government expenditures not exceed total tax revenue and international income transfers, $vb_r$ (ie, the current account balance).

$$\Re_r + vb_r = vgm_r$$

The identities above can also be represented using a social accounting matrix (SAM) framework, as is often done in AGE models. However, the SAM simply provides an alternative method of visualizing the data and is not necessary from a modeling perspective. McDonald and Thierfelder (2004) describe the process for converting the GTAP data into a social accounting matrix.

### 3.2.1 Satellite GTAP Data Sets

An auxiliary land-use data set was developed by Monfreda et al. (2009) specifically for applied general equilibrium analysis using the standard GTAP data set. The GTAP land use data set disaggregates the primary factor demand and endowment arrays ($vfm_{b,a,r}$ and $evom_{b,a,r}$, respectively) to account for heterogeneity in land. While the original data set only includes an aggregate land factor, the satellite data splits land into 18 different agro-ecological zones (AEZ).[10] The disaggregated primary factor arrays do not alter the general equilibrium balance conditions described above. The data set combines a land cover data set

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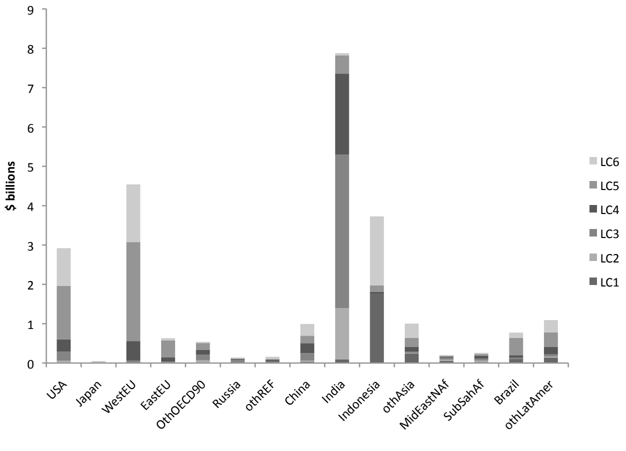
[10] AEZs categorize land by the length of the growing period (LGP), as determined by the moisture regime, and climate zone (temporate, tropical, boreal).

developed by Ramankutty and Foley (1998) at the Center for Sustainability and the Global Environment with global cropland cover data consistent with the GTAP crop categories, developed by Leff et al. (2004). Lee et al. (2009) decompose the aggregate GTAP land rent ($vfm_{\text{land},a,r}$) by AEZ for each commodity and region based on crop output price, harvested acreage, and yield estimates from the United Nations Food and Agriculture Organization. Mathematically,

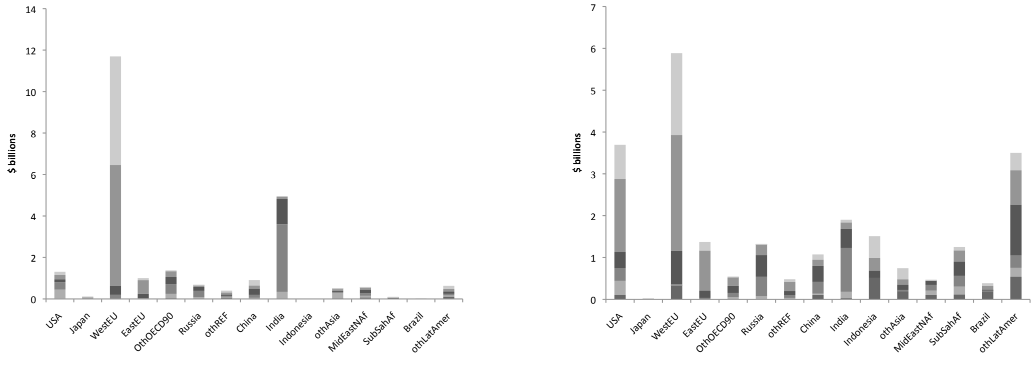
$$vfm_{aez,a,r} = vfm_{\text{land},a,r}\left(\frac{P_a Y_{aez,a} H_{aez,a}}{\sum_{aez} P_a Y_{aez,a} H_{aez,a}}\right)$$

Where $P$, $Y$, and $H$ are the price, yield, and harvested area for GTAP crop category $a$. For illustrative purposes, Figure 3.2 shows the breakdown of land rents (in billions of 2004US dollars) by FARM region and land classification for three key agricultural commodities: oil seeds, wheat, and coarse grains. For simplicity, the 18 AEZs have been aggregated across the three climate zones into 6 land classes.

A second satellite data set tracks energy usage in the economy, which therefore allows for greenhouse gas emissions analysis related to energy production and consumption (McDougall and Aguiar, 2008). Because the energy data is used only as an accounting tool for tracking physical energy usage and $CO_2$ emissions, introducing this data set does not alter the general equilibrium balance conditions. The GTAP energy data base introduces energy quantity information consistent with the existing input-output tables and bilateral trade flows in the benchmark data. Energy volumes, measured in million tons of oil equivalent (MTOE), for five GTAP commodities allow for tracking of energy flows throughout the economy. The five energy commodities ($e \subset c$) are coal, crude oil, natural gas, refined petroleum products (rpp), and electricity. Energy consumption is reported for the benchmark data for firms ($evf_{e,a,r}$), households ($evh_{e,r}$), and bilateral trade ($evt_{e,r,s}$). Total energy consumption, by



(a) Oil Seeds



(b) Wheat (c) Coarse Grains

Figure 3.2: GTAP 7 Benchmark Land Class Values

energy commodity, in region $r$ can therefore be defined as $e_{e,r}^{\text{con}} = \sum_a evf_{e,a,r} + evh_{e,r}$. Total energy production, by energy commodity, in region $r$ is defined as $e_{e,r}^{\text{prod}} = \sum_a evf_{e,a,r} + evh_{e,r} + \sum_s (evt_{e,r,s} - evt_{e,s,r})$.

Tracking the flow of energy volumes from fossil fuel resources in the economy allows for the calculation of $CO_2$ emissions consistent with the GTAP framework. Using carbon emissions coefficients from the IPCC for each energy source, $\lambda_e$, regional upstream $CO_2$ emissions are calculated as:

$$CO2_r = \sum_{e=\text{coal,oil,gas}} \left( e_{e,r}^{\text{con}} \lambda_e \right) + \lambda_{\text{rpp}} \sum_s (evt_{\text{rpp},s,r} - evt_{\text{rpp},r,s})$$

These identities are used below to calculate energy volumes and subsequent $CO_2$ emissions in FARM.

### 3.2.2 FARM Aggregrations

Using all regions and economic sectors provided in the GTAP benchmark data significantly increases model convergence time and is not necessary for most global economic analyses. The GTAP data is therefore aggregated into a smaller subset of regions and sectors pertinent to the analysis. The 113 regions are aggregated to 15 global regions, following the convention set forth by the Stanford Energy Modeling Forum. The 57 economic sectors are aggregated into 37-41 sectors (depending on the requirements for the analysis). Sectoral aggregation decisions were made in order to provide the greatest resolution for the agriculture and energy sectors of the economy. Tables 3.2 and 3.3 details the aggregations used for the various analyses in this dissertation.

## 3.3 Integrating New Sectors

Often times in applied policy analysis, modelers using the GTAP data set may wish to add new economic sectors into the model. To do so requires disaggregating and rebalancing the original value flows so as to obtain the desired information with a new sector while maintaining the equilibrium balance conditions described above.

While a biofuel module containing conventional ethanol and biodiesel activities was introduced into the GTAP data base (Taheripour et al., 2007), this satellite data module was not publicly in the original GTAP 7 product. Furthermore, advanced biofuel sectors have not yet been included as part of the publicly available data.[11] This section details the

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[11] A working paper was recently issued by GTAP providing preliminary details on introducing an advanced biofuel module (Taheripour et al., 2011b). These research efforts have been conducted in parallel to the work in this dissertation.

## Table 3.2: FARM Regional Aggregation (r)

| **GTAP Region** | | **FARM Region** |
|---|---|---|
| Brazil | | Brazil |
| China | Hong Kong | China |
| Taiwan | | |
| Cyprus | Czech Republic | Eastern European Union (eastEU) |
| Estonia | Hungary | |
| Latvia | Lithuania | |
| Malta | Poland | |
| Slovakia | Slovenia | |
| Bulgaria | Romania | |
| India | | India |
| Indonesia | | Indonesia |
| Japan | | Japan |
| Iran | Rest of Western Asia | Middle East & North Africa (MidEastNAf) |
| Egypt | Morocco | |
| Tunisia | Rest of North Africa | |
| Korea | Rest of East Asia | Other Asia (othAsia) |
| Cambodia | Lao | |
| Myanmar | Malaysia | |
| Philippines | Singapore | |
| Thailand | Vietnam | |
| Rest of Southeast Asia | Bangladesh | |
| Pakistan | Sri Lanka | |
| Rest of South Asia | | |
| Mexico | Rest of North America | Other Latin America (othLatAmer) |
| Argentina | Bolivia | |
| Chile | Colombia | |
| Ecuador | Paraguay | |
| Peru | Uruguay | |
| Venezuela | Rest of South America | |
| Costa Rica | Guatemala | |
| Nicaragua | Panama | |
| Rest of Central America | Caribbean | |
| Australia | New Zealand | Other OECD Countries (othOECD90) |
| Rest of Oceania | Canada | |
| Switzerland | Norway | |
| Rest of Europe | Turkey | |
| Rest of EFTA | Albania | Rest of World (othREF) |
| Belarus | Croatia | |
| Ukraine | Rest of Eastern Europe | |
| Kazakhstan | Kyrgyzstan | |
| Rest of Former Soviet Union | Armenia | |
| Azerbaijan | Georgia | |
| Russian Federation | | Russia |
| Nigeria | Senegal | Sub-Saharan Africa (SubSahAf) |
| Rest of Western Africa | Rest of Central Africa | |
| Rest of South Central Africa | Ethiopia | |
| Madagascar | Malawi | |
| Mauritius | Mozambique | |
| Tanzania | Uganda | |
| Zambia | Zimbabwe | |
| Rest of Eastern Africa | Botswana | |
| South Africa | Rest of SAf Customs Union | |
| United States of America | | United State of America (USA) |
| Austria | Belgium | Western European Union (westEU) |
| Denmark | Finland | |
| France | Germany | |
| Greece | Ireland | |
| Italy | Luxembourg | |
| Netherlands | Portugal | |
| Spain | Sweden | |
| United Kingdom | | |

Table 3.3: FARM Commodities (c)

| | Commodity | Notation | GTAP Sectors |
|---|---|---|---|
| Energy Sector | Coal | ecoa | coal |
| | Crude Oil | eoil | oil |
| | Natural Gas | gas | gas, gdt |
| | Electricity | eely | eely |
| Transportation Fuels | Refined Petroleum | ep_c | ep_c |
| | Corn Ethanol | eth1 | N/A |
| | Sugar Cane Ethanol | eth2 | N/A |
| | Other Ethanol | eth3 | N/A |
| | Cellulosic Biofuel | ethcell | N/A |
| Agricultural Sector | Paddy Ride | pdr | pdr |
| | Wheat | wht | wht |
| | Corn | corn | N/A |
| | Other Cereal Grains | gro | gro |
| | Vegetables, Fruits, and Nuts | v_f | v_f |
| | Oil Seeds | osd | osd |
| | Sugar Cane/Beet | c_b | c_b |
| | Plant-Based Fibers | pfb | pfb |
| | Other Crops | ocr | ocr |
| | Cattle, Sheep, Goats, Horses | ctl | ctl |
| | Raw Milk | rmk | rmk |
| | Other Animal Products | oap | oap |
| | Wool | wol | wol |
| | Secondary Corn | cornb | N/A |
| | Switchgrass | swg | N/A |
| | Corn Stover | stover | N/A |
| Other Natural Resource Sectors | Forestry | frs | frs |
| | Fishing | fsh | fsh |
| Industrial Sectors | Food Products | fpr | cmt, omt, vol, mil, pcr, sgr, ofd, b_t |
| | Wood and Paper Products | wpp | lum, ppp |
| | Chemical, Rubber, Plastic Products | crp | |
| | Non-Metalic Minerals | nmm | nmm |
| | Iron and Steel | prim | i_s, nfm |
| | Fertilizer | fert | N/A |
| | Dried Distillers Grains | ddgs | N/A |
| | Other Industrial Products | oid | omn, tex, wap, lea, fmp, mvh, otn, ele, ome, omf, wtr, cns |
| Other Sectors | Transportation | tpt | otp, wtp, atp |
| | Services | svs | trd, cmn, ofi, isr, obs, ros, osg, dwe |

steps required to disaggregate an existing GTAP sector and integrate new economic sectors into the benchmark data. For illustrative purposes, I detail this process with reference to the data used to develop the FARM biofuel module. Further detail on the sources and methods of compiling the data is outlined in Chapter 4.

Disaggregating an existing GTAP sector and creating a new sector follows a 4-step process:

1. Identify the old sector to disaggregate
2. Specify the size of the new sector
3. Specify the technological characteristics of new sector
4. Identify the final demand structure of the new sector

Steps 1 and 2 determine the total value of supply of the new sector, and also the level by which to reduce an existing sector. For example, the total 2004 value of production for the conventional ethanol sector in the U.S. was approximately \$5.547 billion, which reflects a production quantity of 3.409 billion gallons of ethanol fuel, selling at a market price of \$1.63/gallon (this is the 'agent' price and includes any direct industry subsidies). It is assumed that this value was originally captured in "food processing" sector (ofd) in the original GTAP database. The size of this industry is reduced in order to create a new conventional ethanol sector. Table 3.4 outlines the original GTAP sectors used to create each new biofuel sector and Table 3.5 identifies the base year values for each new sector.

A module that captures conventional ethanol production requires creating three new sectors: ethanol production in the U.S. from corn grain with a dried distillers grain with solubles coproduct (eth1), ethanol production in Brazil using sugar cane (eth2), and ethanol production in the EU using wheat and sugar beats (eth3). Refer to Zhou and Kojima (2011) for 2004 biofuel price and quantity information for individual nations. Advanced biofuel production is introduced by creating two new cellulosic feedstock sectors, switchgrass and corn stover, and a new biofuel refining sector that converts these feedstocks into a usable transportation fuel that can be blended with conventional gasoline. The bioelectricity data module (described in Chapter 5) requires a disaggregated electricity sector where cellulosic biomass can be converted directly into electricity.

For advanced biofuel sectors, such as the cellulosic feedstock or refining sectors, a measurable industry did not exist in 2004, the year of the benchmark data. These new sectors are introduced by assuming that a very small industry *did* exist. The size of the industry is assumed to approximately reflect the size of a single commercial cellulosic biofuel refinery and large field-scale cellulosic feedstock production plot. The single refinery is assumed to produce approximately 10 million gallons of biofuel (gasoline equivalents) at a unit cost of $3.17/gallon. These assumptions are shown in Table 3.5. This approach allows for a sector to exist in the modeling framework, without significantly altering other economic sectors or model calibration. Absent any type of policy intervention or dramatic economic changes, the advanced biofuel sectors will remain a negligible component of the economy. However, this approach allows for policy scenarios, such as simulating the U.S. Renewable Fuel Standard, to "grow" these sectors endogenously. Taheripour et al. (2011a) also follow this method for integrating advanced biofuels into the GTAP framework. An alternative method is proposed in Böhringer and Rutherford (2008), with an application to green quotas in the electric power sector.

Table 3.4: Sectoral Disaggregation for New Sectors

|  | Original Sector | New Sectors |
|---|---|---|
| Feedstocks | Wheat (wht) | Wheat (whtn)<br>Switchgrass (swg) |
|  | Corn | Corn<br>Corn w/ Stover (stov) |
| Fuels | Food Processing (ofd) | Food Processing (ofdn)<br>Corn Ethanol (eth1)<br>Other Ethanol (eth3) |
|  | Chemicals etc. (crp) | Chemicals, etc. (crpn)<br>Sugar-Cane Ethanol (eth2)<br>Cellulosic Biofuel (biocell) |

Table 3.5: Base Year Production Assumptions for Various Biofuel Sectors

|  | Fuels |  |  |  | Feedstocks |  |
|---|---|---|---|---|---|---|
|  | Eth1 | Eth2 | Eth3 | Cellulosic | Stover | Switchgrass |
| Quantity[1] | 2.442 | 2.438 | .124 | 0.01 | 105.6 | 70.183 |
| Price[2] | \$2.39 | \$1.12 | \$1.70 | \$3.17 | \$54.71 | \$82.31 |
| Production Value[3] | \$5,833 | \$3,657 | \$210 | \$31.715 | \$5.777 | \$5.777 |

[1] All fuels quantities are reported in billions of gallons of gasoline equivalent. Feedstocks are in 1,000 metric tons.

[2] Reported in 2004\$/unit

[3] 2004 \$millions

Step 3 in the process requires identifying the technological characteristics of each new sector. This information is determined by the cost share of each input as a fraction of total industry output and can be determined from techno-economic assessments of the various sectoral activities. As noted in section 3.2, the zero profit conditions require that the total value of sectoral output, $vom_{a,r}$, must equal the total value of all inputs, $\sum_c (vdfm_{c,a,r} + vifm_{c,a,r}) + \sum_b vfm_{b,a,r}$. The cost share of each intermediate input or primary factor is therefore defined as:

$$\text{cost shares} = \begin{cases} \frac{vdfm_{c,a,r}+vifm_{c,a,r}}{vom_{a,r}} & \text{for intermediate input } c \\ \\ \frac{vfm_{b,a,r}}{vom_{a,r}} & \text{for primary factor } b \end{cases}$$

where $\frac{\sum_c (vdfm_{c,a,r}+vifm_{c,a,r})+\sum_b vfm_{b,a,r}}{vom_{a,r}} = 1$.

The value of each input in the base year is therefore the cost share of a given input multiplied by the base year value of production, identified in Table 3.5. Table 3.6 shows the cost shares for the conventional ethanol and cellulosic biofuel refining industries, as well as the cost shares for the bioenergy feedstocks used in the United States. See Zhou and Kojima (2011) for a detailed breakdown of the unit costs of conventional ethanol production outside of the United States. For agricultural sectors that require cropland, the land satellite data set described above splits the land input into 18 heterogenous categories. A land disaggregation must also be completed for the land factor for any new bioenergy feedstocks sector. Switchgrass is the only new sector that uses land and it is assumed that the AEZ breakdown for switchgrass in the benchmark year is identical to wheat. The assumed base year production quantity for switchgrass assumes that approximately 8,600 hectares of land in used to produce switchgrass. This is simply the approximate acreage required to supply biomass to the 10 million gallon cellulosic biofuel refinery that is introduced into the model. The allocation of this acreage across AEZ is shown in Table 3.7.

Table 3.6: Cost Shares for Bioenergy Feedstocks and Refined Biofuels

| | Bioenergy Feedstocks | | | Fuels | |
|---|---|---|---|---|---|
| | Maize | Switchgrass | Stover | Conventional | Cellulosic |
| Primary Factors | | | | | |
| Labor | 19% | 9% | 20% | 3% | 5% |
| Land | 13.8% | 3.6% | 0.0% | - | - |
| Capital | 16.8% | 40% | 27% | 35% | 26.79% |
| | | | | | |
| Intermediate Inputs[1] | | | | | |
| Fertilizer/Chemicals (fert/crp) | 13% | 21.5% | 25% | - | - |
| Fuel (ep_c) | 3.5% | 2.8% | 10% | - | - |
| Transport (tpt) | 2.9% | 18.3% | 18% | - | - |
| Establishment/Seed (swg) | 1.0% | 2.5% | - | - | - |
| Biomass (corn/swg/stover) | - | - | - | 40% | 36.44% |
| Enzymes (crp) | - | - | - | 8% | 12% |
| Electricity (ele) | - | - | - | 12% | 5% |
| Services (svs) | 16% | - | - | - | - |
| Other[2] | 14% | 2.3% | - | 2% | 14.77% |
| Total | 100% | 100% | 100% | 100% | 100% |

[1] GTAP/FARM sector codes for each input category are in parenthesis.

[2] Other costs include additional business services, refinery construction, and waste disposal.

Table 3.7: Base Year Land Value Shares and Acreage for Switchgrass

| | Land Value Shares | Acreage (ha) |
|---|---|---|
| AEZ1-6 | 0% | 0 |
| AEZ7 | 31.5% | 3,053 |
| AEZ8 | 25.9% | 2,429 |
| AEZ9 | 10.5% | 971 |
| AEZ10 | 15.5% | 1,054 |
| AEZ11 | 11.2% | 711 |
| AEZ12 | 3.5% | 251 |
| AEZ13 | 1.6% | 158 |
| AEZ14 | 0.3% | 24 |
| AEZ15-18 | 0% | 0 |
| Total | 100% | 8,654 |

After specifying the production characteristics of a new industry, the last step (4) is to identify the final demand for each new sector. This must be done in order to satisfy the market clearance conditions of general equilibrium model. Recall that total supply in industry $a$ in the benchmark data, $vom_{a,r}$, is distributed to household and government consumption, firm demand for intermediate inputs, and exports. For cellulosic feedstocks, the total industry supply is used by the cellulosic biofuel industry. For the four biofuel refining sectors, following Taheripour et al. (2007), 75% of the output is used as an intermediate input into the refined petroleum sector, while the remaining 25% is consumed directly by households as a transportation fuel. This assumption reflects the fact that the majority of ethanol is currently used as a gasoline additive, which requires blending with other petroleum products. While there is certainly international trade in biofuels, a simplifying assumption is made to not include trade in this model. This would be limiting if studying a global biofuel expansion and the effects on global oil markets, but here the intention is the isolate the effect of scaling up U.S. production only, and U.S. exports of biofuels have been minimal over the past decade. It is much more pertinent to this analysis to account for trade in agricultural commodities. A detailed breakdown of biofuel trade flows is presented in Zhou and Kojima (2011).

Once the previous information was collected, the GTAP Splitcom program, developed by Horridge (2005), is used to perform the desired disaggregations. Note that this process requires the final product, a new GTAP data set, satisfy the three general equilibrium conditions. Splitcom includes an iterative rebalancing algorithm that satisfies the balance conditions while maintaining the essential value flows in the data set.

### 3.4 Future Agricultural Resources Model

This dissertation uses an applied general equilibrium model of the global economy to assess important questions related to U.S. bioenergy policy. The interconnectedness of global energy and agriculture markets requires a modeling framework that is broad in regional and economic scope, yet provides high enough resolution in agricultural and energy sectors to capture the complex interactions induced by large-scale bioenergy production. This section details the structural equations in the Future Agricultural Resources Model (FARM). While the model was originally constructed using GAMS code provided by Rutherford (2005) as a starting point, and much of the notation and equations are similar, there has been enough model development to justify separately documenting the core model.

FARM is organized in a series of "blocks," representing various agents' behavior, resource allocation, and model closure conditions. The advantage of organizing a large AGE model in this fashion is that it creates a modular platform where different features can be included and excluded as required for the given research question at hand. This section outlines each of these blocks, which includes:

- Block 1: Basic Production
- Block 2: Joint Production
- Block 3: Bilateral Trade
- Block 4: International Transportation Services
- Block 5: Specific (Sluggish) Factors
- Block 6: Household Consumption and Investment
- Block 7: Government Consumption
- Block 8: Energy Consumption and $CO_2$ Emissions
- Block 9: Income Balance and Market Clearing

The first seven blocks detail the key behavioral aspects of the model and each satisfies a set of zero-profit conditions for the relevant markets. Blocks 1-2 describe the producer's problem. Blocks 3-4 describe the treatment of global trade. Block 5 describes the households allocation of sluggish primary factors (land and natural resources) to firms. Block 6-7 describe the optimal consumption and investment bundles for households and the public sector. Block 8 describes the structural equations used to calculate energy usage and the resulting $CO_2$ emissions. Block 9 describes the income balance and market clearing conditions, which ensure that the model includes the proper closure conditions necessary to solve for the Walrasian equilibrium.

Several remarks are necessary in order to follow the notation detailed below. First, all endogenous model variable are denoted using upper-case notation, while all exogenous parameters are denoted using lower-case notation. Second, base year tax rates are denoted using a 'bar' above the parameter, while the absence of a bar indicates that the tax rate may be changed exogenously in a simulation. The same convention holds in several other circumstances which are clear in their respective contexts. Certain model variables are also introduced in the model as endogenous analogous to parameters in the benchmark data set. These variables are denoted in uppercase and begin with a 'D' instead of 'v.' For example, producer demand for domestically produced commodities is designated as '$vdfm$' in the benchmark data set, and '$DDFM$' in FARM model notation. The FARM variables are allowed to vary as a result of exogenous model shocks, and therefore, for the example above, the percentage change in producer demand resulting from a simulation would be $\frac{DDFM - vdfm}{vdfm}$. For definitions of all model variables see Table 3.8.

Section 3.4.10 describes the method for calibrating FARM to the benchmark data set, as well as techniques used to develop baseline scenarios that reflect economic activity beyond the 2004 data. A brief description of model implementation and solution methods is also described.

### 3.4.1 Producer Behavior

The basic production block described here is perhaps the most important methodological component of this dissertation.

Production is described using a nested constant elasticity of substitution (CES) production function. Using a nested CES specification allows for the introduction of input substitution elasticities at any stage of the production process. For simplicity, the standard FARM production structure is introduced here. It is a straightforward, yet messy, calculation

Table 3.8: FARM Primary and Intermediate Variable Definitions

| | | | |
|---|---|---|---|
| Primary Model Variables | | | |
| Activity Levels | | Relative Price Levels | |
| $YA_{a,r}$ | Supply by Activity | $PA_{a,r}$ | Market Price by Activity |
| $YC_{c,r}$ | Supply by Commodity | $PC_{c,r}$ | Market Price by Commodity |
| $M_{c,r}$ | Imports | $PM_{c,r}$ | Composite Import Price |
| $G_r$ | Government Purchases | $PG_r$ | Public Consumption Index |
| $YT_c$ | Transportation Services | $PT_c$ | Price of Transportation Services |
| $FT_{b,r}$ | Specific Factor Transformation | $PF_{b,r}$ | Rental on Primary Factors |
| $INV_r$ | Total Value of Investment | $PS_{b,a,r}$ | Sector-Specific Primary Factor Rental Rate |
| $K_r$ | Capital Stock | $NUM_t$ | Numeraire |
| Income Variables | | Energy and GHG Variables | |
| $RA_r$ | Representative Agent Expenditure | $MTOE_{c,r}$ | Energy Consumption in MTOE |
| $RA_r^{\text{super}}$ | Supernumerary (discretionary) Expenditure | $ECO2_r$ | Regional $CO_2$ Emissions |
| | | $PCO2_r$ | Economy-wide carbon price in region $r$ |
| | | $CTAX_{e,r}^d$ | Carbon tax for each fossil fuel |
| Demand Variables | | | |
| $DDFM_{c,a,r}$ | Producer Demand for Home Goods | $DDPM_{c,a,r}$ | Household Demand for Home Goods |
| $DIFM_{c,a,r}$ | Producer Demand for Imported Goods | $DIPM_{c,a,r}$ | Household Demand for Imported Goods |
| $DFM_{,a,r}$ | Producer Demand for Primary Factors | $DDGM_{c,a,r}$ | Government Demand for Home Goods |
| $DXMD_{c,s,r}$ | Demand for Traded Goods | $DIGM_{c,a,r}$ | Government Demand for Imported Goods |
| $DST_{c,r}$ | Aggregate Demand for Transportation Services | $DTWR_{c,cc,a,r}$ | Demand for Transportation Services |
| Intermediate Variables | | | |
| Unit Cost Functions and Composite Price Indices | | | |
| $c_{a,r}^{y}$ | Domestic Production | $c_{a,r}^{f}$ | Primary Factor Input Composite |
| $c_{c,a,r}^{pf}$ | Primary Factor Inputs | $c_{c,a,r}^{i}$ | Intermediate Inputs |
| $c_{c,r}^{m}$ | Imported Commodities | $c_{c,r}^{G}$ | Aggregate Import Price |
| $c_{c,r}^{HH}$ | Household Consumption | $p_{c,r}^{cm}$ | Government Consumption |

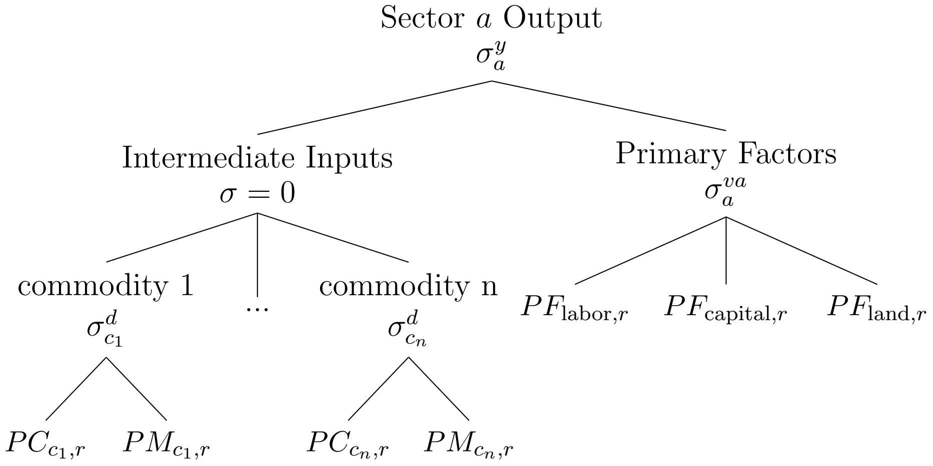

Figure 3.3: Nested CES Production Function

to expand this nesting structure to allow for more flexibility in the bioenergy module. These extensions are described in the analyses performed in the subsequent chapters.

The standard framework specifies a nested production function where in the first nest producers choose the aggregate levels of primary factors and intermediate inputs. The cost of the composite primary factor input is determined by the costs of each individual factor. The cost of the composite intermediate good is determined based on the relative cost of domestically vs. internationally produced commodities. For each imported commodity that can be used in production by domestic industry $a$, an aggregate cost is determined by aggregating the import price for each commodity from a specific trade partner (this is described in more detail in section 3.4.3). The nested production function can be visualized using a nesting tree structure, as shown in Figure 3.3.

For each nest there is an associated unit cost function, and demand function for the composite input.[12] The representative producer's problem in industry $a$ in region $r$ is to

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[12] If the elasticity of substitution for a given nest is zero, no associated price, cost function or demand function need be specified.

select the optimal mix of inputs to maximize profit.[13] Because of the constant returns to scale feature in FARM, the solution to the producer's profit maximization problem is identical to the dual cost minimization problem. Therefore we can write the producer's problem as:

$$\min_{c^i, c^f} \; c^y_{a,r} = \left[ \sum_c \theta^i_{c,a,r} (c^i_{c,a,r})^{1-\sigma^y_a} + \theta^f_{a,r} (c^f_{a,r})^{1-\sigma^y_a} \right]^{\frac{1}{1-\sigma^y_a}}$$

subject to:

$$c^i_{c,a,r} = \left[ \theta^d_{c,a,r} \left( PC_{c,r}(1 + t^{F^d}_{c,a,r}) \right)^{1-\sigma^d_c} + (1 - \theta^d_{c,a,r}) \left( PM_{c,r}(1 + t^{F^m}_{c,a,r}) \right)^{1-\sigma^d_c} \right]^{\frac{1}{1-\sigma^d_c}}$$

$$c^f_{a,r} = \left[ \sum_b \theta^{\mathrm{pf}}_{b,a,r} \left( \frac{c^{\mathrm{pf}}_{b,a,r}}{\bar{P}F_{b,r}} \right)^{1-\sigma^{va}_a} \right]^{\frac{1}{1-\sigma^{va}_a}}$$

$c^y_{a,r}$ is the top level CES unit cost function for industry $a$, which is a function of total unit costs for primary factors, $c^f_{a,r}$, and total unit cost for each intermediate input, $c^i_{c,a,r}$. $\sigma^y_a$ is the elasticity of substitution between intermediate inputs and the primary factor composite.[14] $\theta^i_{c,a,r}$ and $\theta^f_{a,r}$ are the value shares of total industry $a$ output for intermediate goods and primary factors, respectively. $\theta$ parameters are introduced throughout the model and are used to calibrate the structural equations to the GTAP benchmark data set. This is described in detail in section 3.4.10. $\sigma^d_c$ is the elasticity of substitution between domestic and foreign intermediate input $c$ and $\sigma^{va}_a$ is the elasticity of substitution between primary factors for industry $a$.

$PC_{c,r}$ and $PM_{c,r}$ are the equilibrium market commodity prices for domestic and internationally produced goods, without tax distortions. $PM_{c,r}$ is the price for an imported

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[13] The nested CES production function described in Rutherford (2005) does not allow for substitution in the top nest and is therefore presented using more simplified notation. This top nest substitution flexibility is the only difference between the producer behavior blocks the basic version of FARM and GTAPinGAMS.

[14] All default GTAP elasticities, aggregated to the relevant FARM sectors, are reported in Table 3.9 at the end of Section 3.4.

commodity aggregated over all possible trade sources. The determination of $PM_{c,r}$ is described in section 3.4.3. $\theta^d_{c,a,r}$ is the domestic value share for each commodity used as a fraction of the total use of that commodity (domestically produced and foreign). For example if sector $a_1$ uses \$1,000 of commodity $c_2$ in its production process, of which \$600 is purchased from domestic firms, then $\theta^d_{c_2,a_1,r} = 0.6$.

The unit cost function for primary factors, $c^f_{a,r}$, is itself determined by the relative values of each individual primary factor. Because some factors are sector-specific (land and natural resources) and some are perfectly mobile between sectors (labor and capital), the marginal cost for each type of factor must be independently denoted. The unit cost for mobile factors in industry $a$ is defined as:[15]

$$c^{\text{pf}}_{mf,a,r} = c^{\text{pf}}_{mf,r} = PF_{mf,r}(1 + t^{HH}_{mf,a,r})$$

The unit cost for sluggish factors in industry $a$ is defined as:

$$c^{\text{pf}}_{sf,a,r} = PS_{sf,a,r}(1 + t^{HH}_{sf,a,r})$$

Where $PF_{mf,r}$ is the pre-tax equilibrium price of labor and capital, and $PS_{sf,a,r}$ is the pre-tax equilibrium rental rate on land and natural resources. While households can freely allocate labor and capital to the sector with the highest return, land and natural resources are not perfectly mobile between sectors and therefore households must account for this sluggishness in their factor allocation process. The allocation of sluggish factors by households to firms is described in section 3.4.5.

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[15] Intermediate variables, such as nested cost functions and composite prices, are denoted using lower case notation. However, they are technically endogenous variables, but to reduce computational time are implemented using the \$macro command in GAMS. This is acceptable since reporting such variables is not an integral component of model output.

In addition to a unique unit cost function, each nest is also associated with a unique derived input-demand function, resulting from the optimal solution to the producer's minimization problem described above. The three input demand functions associated with the nesting structure described here are as follows:

Primary Factors

$$DFM_{b,a,r} = vfm_{b,a,r} * YA_{a,r}\left(\frac{1}{\phi_{b,a,r}}\right)\left(\frac{\bar{PF}_{b,r}}{c^{\text{pf}}_{b,a,r}} c^{f}_{a,r}\right)^{\sigma^{va}_{a}} \left(c^{y}_{a,r}\right)^{\sigma^{y}_{a}}$$

Domestic Commodities

$$DDFM_{c,a,r} = vdfm_{c,a,r} * YA_{a,r}\left(\frac{1}{\phi_{c,a,r}}\right)\left(\frac{c^{i}_{c,a,r}}{(PC_{c,r}(1+t^{F^d}_{c,a,r}))}\right)^{\sigma^{d}_{c}}\left(\frac{c^{y}_{a,r}}{c^{i}_{c,a,r}}\right)^{\sigma^{y}_{a}}$$

Imported Commodities

$$DIFM_{c,a,r} = vifm_{c,a,r} * YA_{a,r}\left(\frac{1}{\phi_{c,a,r}}\right)\left(\frac{c^{i}_{c,a,r}}{(PM_{c,r}(1+t^{F^m}_{c,a,r}))}\right)^{\sigma^{d}_{c}}\left(\frac{c^{y}_{a,r}}{c^{i}_{c,a,r}}\right)^{\sigma^{y}_{a}}$$

Where $\phi$ is introduced as an exogenous parameter that can be used for policy analysis (and discussed at length in Chapter 4). This parameter has the effect of exogenously shifting the various input demand functions. For example, $\phi$ could be manipulated to exogenously increase demand for biofuel in the refined petroleum sector, or to increase land-use efficiency in the switchgrass sector.

Having derived all of the unit cost and input demand functions for the representative producer in sector $a$, the zero-profit condition for industry $a$, which defines the optimal supply level, $YA_{a,r}$, for that industry, can be written as:

$$cy_{a,r}(\cdot) = PA_{a,r}(1 - t^{y}_{c,r}) \tag{3.1}$$

which states the unit cost of sector $a$ must equal the marginal value of that sector's output, $PA$ (adjusted for any taxes or subsidies in that sector). Establishing the zero-profit condition concludes the discussion of the basic producer problem and the resulting production of goods and services in the economy.

### 3.4.2 Joint Production

The original GTAPinGAMS model does not account for asymmetries in the intermediate input-output flows. The number of economic sectors ($a$) is equal to the number of commodities ($c$) in the economy, which implies that each sector is only capable of producing a single commodity. This assumption is especially restrictive for the biofuels industry. The conventional ethanol refining industry produces both ethanol and distillers grains, while the agricultural residue feedstock industry produces grains as its primary product. The importance of these assumptions on the economic impact of large-scale production has been discussed above.

To incorporate joint production, I introduce a second zero-profit condition to the producer block. While the central equation in the producer's problem states that the marginal benefit of a sectors output ($PA_{a,r}$) must equal its unit cost, for sector's that produce more than one output, we must also establish zero-profit conditions for both the sector and each of its outputs.

Two equations are introduced which split the equilibrium output and price of a multi-commodity market. First, the market clearing supply of commodity $c$ is specified using a constant elasticity of transformation function to specify the split of sector $a$'s total output value between its various products.

$$YC_{c,r} = \sum_{\text{map-ac}} \left( \frac{YA_{a,r} * PA_{a,r}}{PC_{c,r}} \right)^{\eta_a^{\text{jp}}}$$

|  | $a_1$ | $a_2$ |
|---|---|---|
| $c_1$ | x |  |
| $c_2$ |  | x |

(a) Standard

|  | $a_1$ | $a_2$ |
|---|---|---|
| $c_1$ | x |  |
| $c_2$ |  | x |
| $c_3$ |  | x |

(b) Joint Products

Figure 3.4: Commodity/Sector Mapping

Where $\eta_a^{\text{jp}}$ is the elasticity of transformation between joint products in sector $a$. $\eta_a^{\text{jp}} = 0$ if the sector produces only one commodity or it's joint products are fixed coefficient.

map-ac is a mathematical operator that maps commodities to sectors. In the original modeling framework, map-ac linked each commodity to a single industry. The mapping for joint commodity sectors identifies which commodities are associated with each sector. For example, in Table 3.4, panel (a) shows the original mapping of a single commodity to a single sector, while panel (b) shows that sector $a_2$ produces two commodities, $c_2$ and $c_3$.

In joint-product sectors, the zero-profit condition defined in the producer block must be modified to impose this condition on each *commodity* that the sector produces. The market-clearing price for joint-product sector $a$ is therefore decomposed into two commodity prices according to the share of output that each commodity contributes to total sector output value. Each commodity price must also satisfy the zero-profit conditions. Mathematically, this is written as:

$$PA_{a,r} = \sum_{\text{map-ac}} \left( \theta_{c,r}^{\text{jp}} PC_{c,r}^{1-\eta_a^{\text{jp}}} \right)^{\frac{1}{1-\eta_a^{\text{jp}}}} \tag{3.2}$$

Where $\theta_{c,r}^{\text{jp}} = \frac{vom_{c,r}^{\text{c}}}{\sum_c vom_{c,r}^{\text{c}}}$, and is interpreted as the value of a single commodity output in sector $a$ as a fraction of sector $a$'s total output. $\theta_{c,r}^{\text{jp}} = 1$ and $\eta_a^{\text{jp}} = 0$ for sectors that only produce a single commodity, and therefore $PA_{a,r} = PC_{c,r}$ in equilibrium.

### 3.4.3 Bilateral Trade

Aggregate imports of commodity $c$ in region $r$ are determined by the unit costs of production in region $s$ plus the costs of transportation from region $s$ to region $r$. Many global trade models, including those that rely on the GTAP data set, apply an Armington product-differentiation framework (Armington, 1969).

This concept it modeled using an elasticity of substitution, $\sigma_c^m$, between regions for commodity $c$. The representative agent's problem (households, firms, and the government) is therefore to minimize unit costs for imported commodity $c$, factoring in global transportation margins. Mathematically,

$$\min_{DXMD,DTWR} \sum_{c,s} (1 - t^M_{c,s,r}) \left( PC_{c,s} * (1 - t^x_{c,s,r}) DXMD_{c,s,r} + \sum_a PT_c * DTWR_{c,a,s,r} \right)$$

The aggregated price of an imported commodity from region $s$ into region $r$ is a composite of the price of the commodity in the exporting region, $PC_{c,s}$, any export subsidies and import tariffs, and the transportation margins for that commodity. This aggregate price can be written as:

$$p^{cm}_{c,s,r} = \theta^{\text{vxmd}}_{c,s,r} PC_{c,s} \left[ \frac{(1 - t^X_{c,s,r})(1 + t^M_{c,s,r})}{(1 - \bar{t}^X_{c,s,r})(1 + \bar{t}^M_{c,s,r})} \right] + \sum_{cc} \theta^{\text{vtwr}}_{cc,c,s,r} PT_c \left[ \frac{(1 + t^M_{cc,s,r})}{(1 - \bar{t}^X_{cc,s,r})(1 + \bar{t}^M_{cc,s,r})} \right]$$

Where $\theta^{\text{vxmd}}_{c,s,r}$ and $\theta^{\text{vtwr}}_{cc,c,s,r}$ are the value shares in the benchmark data of the commodity and transportation margins, respectively, in the composite price of imported commodity $c$.

The unit cost function for imported commodity $c$ into region $r$ is therefore:

$$c^m_{c,r} = \left[ \sum_s \theta^M_{c,s,r} \left( p^{cm}_{c,s,r} \right)^{1-\sigma^m_c} \right]^{\frac{1}{1-\sigma^m_c}}$$

and the demand for imported commodity from region $s$ is:

$$DXMD_{c,s,r,} = \left( vxmd_{c,s,r} * M_{c,r} * \frac{PM_{c,r}}{p^{cm}_{c,s,r}} \right)^{\sigma^m_c}$$

and the demand for transportation services is:

$$DTWR_{cc,c,s,r,t} = \left( vtwr_{cc,c,s,r} * M_{c,r} * \frac{PM_{c,r}}{p^{cm}_{c,s,r}} \right)^{\sigma^m_c}$$

The zero-profit condition for traded commodities (excluding taxes and transportation margins), defining the optimal level of aggregate imports, $M_{c,r}$, is therefore:

$$c^m_{c,r}(\cdot) = PM_{c,r} \tag{3.3}$$

where $PM_{c,r}$ is the import price of commodity $c$ in region $r$.

### 3.4.4 International Transportation Services

To account for transportation margins in international trade ($vtwr_{c,r,s}$), an transportation service sector is modeled that aggregates total payments for such services across regions. These payments are important as they affect the import price of a traded commodity. For simplicity, these services are modeled using a Cobb-Douglas cost function, where the producer's problem is to choose a level of international transportation services that minimizes the cost of these services.

$$\min_{DST_{c,r}} PC_{c,r} * DST_{c,r} \text{ subject to } YT_c = \sum_{c,r,s} DTWR_{c,cc,r,s}$$

Solving this minimization yields an commodity-specific demand function for transportation services in each region, donated as:

$$DST_{c,r} = \frac{vst_{c,r} * YT_c * PT_c}{PC_{c,r}}$$

where $PT_c$ is the world price of transportation services

The zero-profit condition for international transportation services, which defines the optimal output level, $YT_c$, is therefore satisfied when the marginal cost, $PT_c$, is equal to the marginal value.

$$PT_c = \prod_r (PC_{c,r}^{\frac{vst_{c,r}}{vt_c}}) \tag{3.4}$$

### 3.4.5 Sluggish Factor Transformation

Certain factors of production are not easily converted from one productive use to another. As such, the marginal value of these factors does not adjust perfectly to changes in relative output prices. For example, while land can be allocated to multiple productive uses, any reallocation is likely to be costly or happen over a period of time longer than the reallocation of factors like labor and capital. To model this "sluggish" reallocation, FARM employs a constant elasticity of transformation function (CET) to specify the ability of such factors to move across economic sectors as a result of changing relative prices. Households, who own the primary factors of production, are faced with the following maximization problem:

$$\max_{DFM} \sum_a DFM_{sf,a,r} * PS_{sf,a,r}$$

$$\text{subject to } \; FT_{sf,a,r} = \left[\theta^{\text{vfm}}_{sf,a,r} DFM^{1+\eta_{sf}}_{sf,a,r}\right]^{\frac{1}{1+\eta_{sf}}}$$

Where $FT_{b,a,r}$ is the constant elasticity of transformation revenue function and $PS_{sf,r}$ is the marginal value for each sluggish factor for each sectors. $\theta_{sf,a,r}$ is the value share of each sluggish factor in sector $a$ relative to the total sluggish factor endowment in that sector, calibrated from the benchmark data.

$$\theta_{sf,a,r} = \frac{vfm_{sf,a,r}}{evom_{sf,r}}$$

The profit maximizing allocation of sluggish factors is therefore determined by the aggregate price across possible uses, accounting for the elasticity of transformation between economic sectors. Solving this maximization problem, the zero-profit condition in the market for sluggish factors can be written as:

$$PF_{sf,r} = \left[ \sum_{a} \theta^{\text{vfm}}_{sf,a,r} * PS^{1+\eta_{sf}}_{sf,a,r} \right]^{\frac{1}{1+\eta_{sf}}} \tag{3.5}$$

which defines the optimal allocation of sluggish factors, $FT_{b,r}$, in the economy

While this formulation is general enough to handle any specific factor, the application to land allocation is especially important for bioenergy applications. As discussed in Chapter 2, there are several methods for modeling land allocation in an applied general equilibrium framework, and the CET methodology has been well established in the literature (see Hertel et al., 2009b). The method used in this analysis is a simplification of the approach used by Hertel et al. (2009a). As shown in Figure 3.5, for each land class or agroecological zone ($k$), households allocate the land to crop production, grazing operations, or forestry. While the total land available in a given AEZ is fixed, the allocation of that land class to productive uses is constrained by $\eta_{sf}$, the elasticity of transformation described above. For a given AEZ, land allocation in response to exogenous shocks is largely driven by the assumed $\eta_{sf}$ value. For this study, a relatively inelastic land supply parameter is used based on estimates in the literature ($\eta_{sf} = 0.5$ for all AEZs). Measuring accurate land response and sectoral response elasticities is an important area of future research, particularly for cellulosic bioenergy feedstocks such as perennial grasses.

### 3.4.6 Household Consumption

Household income is allocated to the consumption of commodities and savings. Regional households make expenditure decisions in order to maximize utility, $U_r$, subject to a budget constraint. This is analogous to a cost minimization problem subject to the constraint

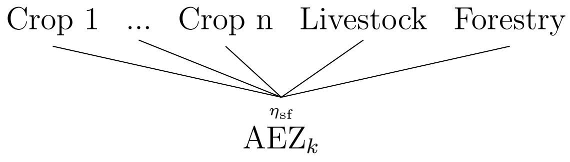

Figure 3.5: AEZ Land Allocation

that all income is exhausted. FARM uses the linear expenditure system (LES) specification (Stone, 1954), as opposed to the GTAPinGAMS model which uses a CES consumer demand approach. This allows for the specification of minimum consumption levels of a given commodity in the consumer's bundle. The household's problem, assuming a Stone-Geary unit cost function, can be written as:

$$\begin{aligned}
\min_{DDPM,DDIM} &= \Bigg(\alpha^d_{c,r} DDPM_{c,r} * \Big(PC_{c,r} * (1 + t^{P^d}_{c,r})\Big)^{1-\sigma^d_c} \\
&\quad + \alpha^i_{c,r} DDIM_{c,r} * \Big(PM_{c,r} * (1 + t^{P^m}_{c,r})\Big)^{1-\sigma^d_c}\Bigg)^{\frac{1}{1-\sigma^d_c}} \\
\text{subject to } RA^{\text{super}}_r &= RA_r - \sum_c \gamma_{c,r} * vdpm_{c,r} * PC_{c,r} * (1 + t^{P^d}_{c,r}) \\
&\quad - \sum_c \gamma_{c,r} * vipm_{c,r} * PM_{c,r} * (1 + t^{P^m}_{c,r})
\end{aligned}$$

Where $RA_r$ is total household expenditure, which is equated later to the payments to primary factors from productive sectors of the economy. $\gamma_{c,r}$ is interpreted as the minimum (or subsistence) expenditure for good $c$. $RA^{\text{super}}_r$ is the supernumerary (or discretionary) income available after subsistence expenditure levels have been met.

Solving this constrained optimization, unit costs for the household are given by:

$$c^{HH}_{c,r} = \left[\theta^{HH^d}_{c,r} * \Big(PC_{c,r} * (1 + t^{P^d}_r)\Big)^{1-\sigma^d_c} + \theta^{HH^i}_{c,r} * \big(PM_{c,r} * (1 + t^{P^m}_r)\big)^{1-\sigma^d_c}\right]^{\frac{1}{1-\sigma^d_c}}$$

which reflects the ability of the household to substitute between domestic and imported goods according to the CES parameter, $\sigma^d_c$. $\theta^{HH^d}_{c,r}$ and $\theta^{HH^i}_{c,r}$ are the domestic and imported commodity value shares, where $\theta_{c,r}^{HH^d} + \theta_{c,r}^{HH^i} = 1$ for each commodity consumed by the household.

The first order conditions of the household's cost minimization problem also defines optimal expenditures (demand) on domestic/imported goods and are given (in respective order) by:

$$DDPMc,r = \gamma_{c,r} * vdpm_{c,r} + \left[\alpha_{c,r}^{d} \frac{RA_r^{super}}{c_{c,r}^{HH}(\cdot) * (1 + t_{c,r}^{Pd})} * \frac{c_{c,r}^{HH}(\cdot)}{PC_{c,r} * (1 + t_{c,r}^{Pd})}\right]^{\sigma_c^d}$$

$$DIPMc,r = \gamma_{c,r} * vipm_{c,r} + \left[\alpha_{c,r}^{i} \frac{RA_r^{super}}{c_{c,r}^{HH}(\cdot) * (1 + t_{c,r}^{Pm})} * \frac{c_{c,r}^{HH}(\cdot)}{PM_{c,r} * (1 + t_{c,r}^{Pm})}\right]^{\sigma_c^d}$$

$\alpha_{c,r}$ is the budget share of good $c$ in the household's consumption bundle. Note that budget shares are divided between domestic goods, $\alpha_{c,r}^d$, and imported goods, $\alpha_{c,r}^i$. These two demand equations define the household's optimal consumption bundle.

The zero profit condition for the household is defined as:

$$RA_r^{\text{super}} = RA_r - \sum_c \gamma_{c,r} vdpm_{c,r} PC_{c,r}(1 + t_{c,r}^{Pd}) - \sum_c \gamma_{c,r} vipm_{c,r} PM_{c,r}(1 + t_{c,r}^{Pm}) \qquad (3.6)$$

which simply says that total discretionary expenditures must equal total expenditures less the value of all goods consumed by the household at the subsistence level.

Household savings (or investment), defined as $vdim_{c,r}$ in the benchmark data, is introduced into the model as a commodity from which households derive utility. In the model, aggregate savings levels, $INV_r$, are exogenously fixed based on investment levels in the benchmark data, adjusted for changes in relative price levels. Mathematically,

$$INV_r = \frac{\sum_c vdim_{c,r}}{vpm_r} RA_r \qquad (3.7)$$

This set of equations defines the optimal consumption (for each commodity) and investment levels for the representative household in region $r$.

### 3.4.7 Government Consumption

Government expenditure on commodities is determined by a fixed-coefficient aggregation of domestically purchased commodities and imported commodities. Government utility is maximized at the consumption bundle that minimizes unit costs, which are denoted as:

$$c^G_{c,r} = \left[\theta^{G^d}_{c,r}\left(PC_{c,r}\frac{1+t^{G^d}_{c,r}}{1+\bar{t}^{G^d}_{c,r}}\right)^{1-\sigma^d_c} + \theta^{G^i}_{c,r}\left(PM_{c,r}\frac{1+t^{G^m}_{c,r}}{1+\bar{t}^{G^m}_{c,r}}\right)^{1-\sigma^d_c}\right]^{\frac{1}{1-\sigma^d_c}}$$

Where $\theta^{G^d}_{c,r}$ and $\theta^{G^i}_{c,r}$ are the calibrated domestic and import shares of government expenditures for commodity $c$. $\sigma^d_c$ is the elasticity of substitution between home goods and imports, which are identical to the elasticities presented in the producer and household blocks.

Government demand for domestically produced and imported goods is given by:

$$DDGM_{c,r} = vdgm_{c,r}G_r\left(\frac{c^G_{c,r}(\cdot)}{PC_{c,r}\frac{1+t^{G^d}_{c,r}}{1+\bar{t}^{G^d}_{c,r}}}\right)^{\sigma^d_c}$$

$$DIGM_{c,r} = vigm_{c,r} * G_r\left(\frac{c^G_{c,r}(\cdot)}{PM_{c,r}\frac{1+t^{G^m}_{c,r}}{1+\bar{t}^{G^m}_{c,r}}}\right)^{\sigma^d_c}$$

The zero-profit condition implies that government expenditures, $G_r$, are defined where the marginal value of public consumption equals the unit cost of public consumption.

$$PG_r = \sum_c \theta_{c,r}c^G_{c,r}(\cdot) \tag{3.8}$$

### 3.4.8 Energy Consumption and $CO_2$ Emissions

Upstream energy consumption (millions of tons of oil equivalent) and associated $CO_2$ emissions are calculated based on energy commodities ($e \subset c$) production levels determined endogenously in FARM. These values are represented as identities based on optimizating behavior from economic agents.

Energy levels are split into consumption from domestic sources (D) and imports (M), defined respectively as:

$$\begin{aligned}
MTOE^{D}_{e,r} =& e^{\text{prod}}_{e,r} \frac{\sum_a DDFM_{e,a,r} + DDPM_{e,r} + DDGM_{e,r} + DDIM_{e,r}}{vom_{e,r}} \\
MTOE^{M}_{e,r} =& e^{\text{prod}}_{e,r} \frac{\sum_s DXMD_{e,s,r} + DST_{e,r}}{vom_{e,r}}
\end{aligned}$$

Total domestic energy consumption in region $r$ is therefore defined as:

$$MTOE_{ec,r} = MTOE^{D}_{ec,r} + MTOE^{M}_{ec,r} \tag{3.9}$$

Regional $CO_2$ emissions from the consumption of fossil fuels are calculated as:

$$ECO2_r = 0.041868 * \sum_{e=\text{coal,oil,gas}} (MTOE_{e,r}\lambda_e) + \lambda_{\text{rpp}} \sum_s (MTOE_{\text{rpp},s,r} - YC_{\text{rpp},r} e^{\text{prod}}_{\text{rpp},r})$$

$CO_2$ emissions factors are taken from Table 1.4 of International Panel on Climate Change (2006) with the following values: coal, 98.3; crude oil, 73.3; natural gas, 56.1, and refined petroleum; 73.3.[16] Note that for unrefined energy commodities (coal, crude oil, and natural gas), emissions are calculated based on total upstream consumption. However, for refined petroleum, which is a secondary energy product, emissions are calculated based on net consumption (consumption-production) to avoid double counting domestically produced crude oil used in by the transportation fuel blending sector.

In Chapter 5 a GHG emissions policy is simulated in order to evaluate the impact on various bioenergy production pathways. An endogenous price for carbon, $PCO2_r$, is determined according the reduction target, $\Theta$, in region $r$:

$$\Theta_r \geq ECO2_r \tag{3.10}$$

---

[16] A conversion factor of 0.041868 is needed to convert units from joules (as reported by the IPCC) to millions tons of oil equivalents, as used by FARM.

$PCO_{2r}$ can then be translated from an economy-wide emissions price into a sector specific tax on fossil fuel use based on the carbon content of each specific energy carrier.

$$CTAX^{d}_{e,a,r} = PCO2_r * \kappa_{e,r} \tag{3.11}$$

$\kappa_{e,r}$ translates the carbon price (\$ per unit of emissions) into a price per unit of energy content for energy commodity $e$.

$$\kappa_{e,r} = 0.041868 * \frac{1}{\lambda_e} * \frac{e^{\text{prod}}_{e,r}}{vom_{e,r}}$$

Equilibrium commodity prices, $PC_{e,r}$, for energy commodities are then increased by the endogenously determined carbon price.

### 3.4.9 Market Clearance and Income Balance

Satisfying the Walrasian general equilibrium conditions requires that all markets in the model clear, income balance is satisfied, and all markets satisfy the zero economic profit condition. Only the latter has been specified thus far, and I therefore now turn to describing the market clearance and income balance conditions in FARM.

Market clearing conditions in the model are directly analogous to the market clearance conditions described in Section 3.2, except that changes from the benchmark data must be accounted for. Each market clearing condition defines the vector of equilibrium prices for that market. To illustrate this comparison, recall that using the benchmark data, the market clearing condition for domestic commodity markets is defined as:

$$vom_{a,r} = vdpm_{c,r} + vdgm_{c,r} + \sum_{a} vdfm_{c,a,r} + \sum_{s} vxmd_{c,r,s} + vdim_{c,r} + vst_{c,r}$$

Using variables introduced this far, the domestic commodity market clearance condition in the model is defined as:

$$\begin{aligned} YC_{c,r,t} * vom\_c_{c,r,t} = & \sum_{c}(DDPM_{c,r,t} + DDGM_{c,r,t} + DDFM_{c,a,r,t}) \\ & + \sum_{s} DXMD_{c,r,s,t} + DDIM_{c,r,t} + DST_{c,r,t} \end{aligned} \tag{3.12}$$

Clearly, the two are quite similar except that exogenous parameters have been replaced by their endogenous model analogues, and relative variables (in this case output in sector $c$) are introduced to scale the base year data after a simulation is performed. Understanding this analogy, the remaining market clearing conditions are defined as follows:

Primary Factors

$$evom_{b,r} = evom_{sf,r} * FT_{f,r} + \sum_{a} DFM_{mf,a,r} \tag{3.13}$$

Sluggish Factors

$$vfm_{sf,a,r} * \left[\frac{PS_{sf,a,r}}{PF_{sf,r}}\right]^{\eta_{sf}} = DFM_{sf,a,r} \tag{3.14}$$

Aggregate Imports

$$M_{c,r} * vim_{c,r} = \sum_{a} DIFM_{c,a,r} + DIPM_{c,r} + DIGM_{c,r} \tag{3.15}$$

Transportation Services

$$YT_{c} * vtr_{c} = \sum_{cc,r,s} DTWR_{c,cc,r,s} \tag{3.16}$$

The income balance conditions require that household and government expenditures not exceed income, and in fact this relationship must hold with strict equality. For the representative household in region $r$, the income balance condition requires that:

$$RA_{r} + \sum_{c} PC_{c,r} * DDIMc,r = \sum_{mf,a} DFM_{mf,a,r} * PF_{mf,r} + \sum_{sf,a} DFM_{sf,a,r} * PS_{sf,a,r} \tag{3.17}$$

Government expenditures must also not exceed total tax revenue plus transfers from abroad.

$$G_r = \text{NUM} * \text{vb}_r + \Re_r^o + \Re_r^{F^d} + \Re_r^{F^i} + \Re_r^{P^d} + \Re_r^{P^i} + \Re_r^{G^d} + \Re_r^{G^i} + \Re_r^x + \Re_r^m \tag{3.18}$$

Equations 3.1-3.18 provide the structural foundations for the FARM model.

Table 3.9: GTAP Default Elasticities

| | $\sigma_c^d$ | $\sigma_c^m$ | $\sigma_c^{va}$ |
|---|---|---|---|
| ecoa | 3.05 | 6.10 | 0.20 |
| eoil | 5.20 | 10.40 | 0.20 |
| egas | 10.61 | 32.59 | 0.66 |
| ep_c | 2.10 | 4.20 | 1.26 |
| eely | 2.80 | 5.60 | 1.26 |
| pdr | 5.05 | 10.10 | 0.24 |
| wht | 4.45 | 8.90 | 0.24 |
| corn, gro | 1.30 | 2.60 | 0.24 |
| v_f | 1.85 | 3.70 | 0.24 |
| osd | 2.45 | 4.90 | 0.24 |
| c_b | 2.70 | 5.40 | 0.24 |
| pfb, ocr | 3.12 | 6.18 | 0.24 |
| ctl, rmk | 2.86 | 4.08 | 0.24 |
| oap | 1.30 | 2.60 | 0.24 |
| wol | 6.45 | 12.90 | 0.24 |
| frs | 2.50 | 5.00 | 0.20 |
| fsh | 1.25 | 2.50 | 0.20 |
| fpr | 2.47 | 4.98 | 1.12 |
| wpp | 3.10 | 6.33 | 1.26 |
| crp, frt | 3.30 | 6.60 | 1.26 |
| nmm | 2.90 | 5.80 | 1.26 |
| prim | 3.42 | 7.12 | 1.26 |
| oid | 3.19 | 7.52 | 1.29 |
| tpt | 1.90 | 3.80 | 1.68 |
| svs | 1.90 | 3.80 | 1.34 |

### 3.4.10 Calibrating and Solving FARM

Equations 3.1-3.18 define structural features of the FARM model. In order to solve the model for a given GTAP benchmark data set, the structural equations in the model must be calibrated to that data. As mentioned in section 3.4.1, this involves using the benchmark data arrays and identities to define the $\theta$ parameters introduced throughout the model. Table 3.10 defines all value shares identified above necessary to calibrate the FARM model.

The parameters defined in Table 3.10 will calibrate FARM to the 2004 GTAP data set. For policy analysis, the researcher may also be interested in using exogenous factors

Table 3.10: Calibrated Value Shares for Benchmark GTAP 7 Data

| | |
|---|---|
| Production, Joint Product, and Specific Factor Blocks | |
| Firm Intermediate Share | $\theta^{i}_{c,a,r} = \frac{vdfm_{c,a,r}(1+\bar{t}^{F^d}_{b,a,r})+vifm_{c,a,r}(1+\bar{t}^{F^m}_{b,a,r})}{vom_{a,r}(1-\bar{t}^{y}_{a,r})}$ |
| Firm Primary Factor Share | $\theta^{f}_{b,r} = \frac{\sum_b vfm_{b,a,r}(1+\bar{t}^{HH}_{b,a,r})}{vom_{a,r}(1-\bar{t}^{y}_{a,r}}$ |
| Joint Product Share | $\theta^{\text{jp}}_{c,r} = \frac{vom^{c}_{c,r}}{\sum_{\text{map-ac}} vom_{a,r}}$ |
| Firm Primary Factor Share | $\theta^{pf}_{b,a,r} = \frac{vfm_{b,a,r}(1+\bar{t}^{HH}_{b,a,r})}{\sum_b vfm_{b,a,r}(1+\bar{t}^{HH}_{b,a,r})}$ |
| Firm Domestic Good Share | $\theta^{d}_{c,a,r} = \frac{vdfm_{c,a,r}(1+\bar{t}^{F^d}_{b,a,r})}{vdfm_{c,a,r}(1+\bar{t}^{F^d}_{b,a,r})+vifm_{c,a,r}(1+\bar{t}^{F^m}_{b,a,r})}$ |
| Specific Factor Value Share | $\theta^{\text{vfm}}_{sf,a,r} = \frac{vfm_{sf,a,r}}{evom_{sf,r}}$ |
| Bilateral Trade Block | |
| Import Composite Share | $\theta^{M}_{c,s,r} = \frac{vxmd_{c,s,r}(1+\bar{t}^{M}_{c,r,s})(1-\bar{t}^{X}_{c,r,s})+\sum_{cc} vtwr_{cc,c,s,r}(1+\bar{t}^{M}_{c,r,s})}{vim_{c,r}}$ |
| Import Share | $\theta^{\text{vxmd}}_{c,s,r} = \frac{vxmd_{c,s,r}(1+\bar{t}^{M}_{c,r,s})(1-\bar{t}^{X}_{c,r,s})}{vxmd_{c,s,r}(1+\bar{t}^{M}_{c,r,s})(1-\bar{t}^{X}_{c,r,s})+\sum_{cc} vtwr_{cc,c,s,r}(1+\bar{t}^{M}_{c,r,s})}$ |
| Transportation Service Share | $\theta^{\text{vtwr}}_{cc,c,s,r} = \frac{vtwr_{cc,c,s,r}(1+\bar{t}^{M}_{c,r,s})}{vxmd_{c,s,r}(1+\bar{t}^{M}_{c,r,s})(1-\bar{t}^{X}_{c,r,s})+\sum_{cc} vtwr_{cc,c,s,r}(1+\bar{t}^{M}_{c,r,s})}$ |
| Household and Government Consumption Blocks | |
| HH Domestic Good Share | $\theta^{HH^d}_{c,r} = \frac{vdpm_{c,r}*(1+\bar{t}^{P^d}_{c,r})}{vdpm_{c,r}*(1+\bar{t}^{P^d}_{c,r})+vipm_{c,r}*(1+\bar{t}^{P^m}_{c,r})}$ |
| HH Import Good Share | $\theta^{HH^m}_{c,r} = \frac{vipm_{c,r}*(1+\bar{t}^{P^m}_{c,r})}{vdpm_{c,r}*(1+\bar{t}^{P^d}_{c,r})+vipm_{c,r}*(1+\bar{t}^{P^m}_{c,r})}$ |
| Supernumerary Expenditure Shares | |
| Domestic Goods | $\alpha^{d}_{c,r} = \frac{(1-\gamma_{c,r})*vdpm_{c,r}*(1+\bar{t}^{P^d}_{c,r})}{RA^{super}_{r}}$ |
| Imported Goods | $\alpha^{m}_{c,r} = \frac{(1-\gamma_{c,r})*vipm_{c,r}*(1+\bar{t}^{P^m}_{c,r})}{RA^{super}_{r}}$ |
| Gov't Domestic Good Share | $\theta^{G^d}_{c,r} = \frac{vdgm_{c,r}*(1+\bar{t}^{G^d}_{c,r})}{vdgm_{c,r}*(1+\bar{t}^{G^d}_{c,r})+vigm_{c,r}*(1+\bar{t}^{G^m}_{c,r})}$ |
| Gov't Import Good Share | $\theta^{G^i}_{c,r} = \frac{vigm_{c,r}*(1+\bar{t}^{G^m}_{c,r})}{vdgm_{c,r}*(1+\bar{t}^{G^d}_{c,r})+vigm_{c,r}*(1+\bar{t}^{G^m}_{c,r})}$ |
| Agg. Gov't Commodity Share | $\theta^{G}_{c,r} = \frac{vdgm_{c,r}*(1+\bar{t}^{G^d}_{c,r})+vigm(c,r)*(1+\bar{t}^{G^m}_{c,r})}{\sum_c \left(vdgm_{c,r}*(1+\bar{t}^{G^d}_{c,r})+vigm(c,r)*(1+\bar{t}^{G^m}_{c,r})\right)}$ |

to 'update' the model in order to represent the economy after 2004. This is often referred to as establishing a baseline scenario or projection, against which to compare a specific policy scenario. The calibrated model is updated using information on labor productivity, population growth and energy efficiency for each region. Assumed annual labor productivity, population growth, and energy efficiency growth rates are shown in Table 3.11.[17] Labor productivity changes are implemented by exogenously shifting the labor demand curves for all sectors in each region by the specified growth rate. Recall that the primary factor demand function, specified in section 3.4.1 is:

$$DFM_{b,a,r} = vfm_{b,a,r} * YA_{a,r} \left( \frac{1}{\phi_{b,a,r}} \right) \left( \frac{\bar{P}F_{b,r}}{c^{\text{pf}}_{b,a,r}} c^{f}_{a,r} \right)^{\sigma^{va}_{a}} \left( c^{y}_{a,r} \right)^{\sigma^{y}_{a}}$$

Higher values of $\phi_{\text{labor},a,r}$ represent larger labor productivity improvements and shift the labor demand curve inwards. For example, a 1% annual increase in labor productivity in region $r$ corresponds to $\phi_{\text{labor},a,r} = 1.01$ and decreases labor demand in region $r$ by 0.99% $(1 - \frac{1}{1.01})$. To update to model from the benchmark year, $t_0$=2004 to $t_1$, simply multiply $\phi_{\text{labor},a,r}$ by $t_1 - t_0$.

Energy efficiency improvements follow a similar process, except that is assumed that firm demand for primary energy products (coal, oil, and natural gas) and electricity changes exogenously based on the energy efficiency rates in Table 3.11. Using the intermediate input demand functions specified in section 3.4.1, $\phi_{ec,a,r}$ is set to either 1.01 or 1.02, which shifts the demand for energy commodities in each sector down by 1-2% per year. This updating procedure is based on the general observation that as nations develop, total and per capita energy use as a fraction of gross domestic product tends to decline (Schmalensee et al., 1998).

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[17] Labor productivity and energy efficiency estimates in this version of FARM are highly stylized and meant only to reflect general possible trends. Integrating more accurate estimates in an important area of future work. Population growth estimates are based on United Nations (2008) projections.

Table 3.11: Macroeconomic Model Updating Assumptions (annual percentage changes)

| | Labor Productivity | Population Growth | Energy Efficiency |
|---|---|---|---|
| USA | 1 | 0.95 | 1 |
| WestEU | 0.5 | 0.41 | 1 |
| EastEU | 1 | -0.13 | 1 |
| Japan | 0.5 | -0.14 | 1 |
| othOECD90 | 0.5 | 1.20 | 1 |
| China | 3 | 0.75 | 2 |
| India | 3 | 1.42 | 2 |
| Indonesia | 1 | 1.30 | 1 |
| OthAsia | 1 | 1.52 | 1 |
| MidEastNAf | 1 | 2.19 | 1 |
| SubSahAf | 2 | 2.14 | 1 |
| Brazil | 2 | 0.94 | 1 |
| othLatAmer | 1 | 1.77 | 1 |
| Russia | 1 | -0.30 | 2 |
| othREF | 1 | -0.07 | 2 |

As shown in Table 3.11, population growth varies considerably throughout the regions in the model. These population rates are used in the model to exogenously shift the labor supply curve in proportion to population changes. This makes a simplifying assumption that changes in the labor force are proportional to changes in population. Adding to (or subtracting from) the labor force changes the initial labor endowment in the model and allows for primary factor substitutions to occur. Using the notation established above, $evom_{\text{labor,r}}$ is multiplied by the population growth rates to adjust the labor factor endowment. Production levels in the base year are also adjusted by the population growth rate, in order to reflect population driven changes in demand for goods and services. For example, sector $a$'s output, $YA_{a,r}$ is set to 1 for model calibration *without* any population changes factored in. This would calibrate the model's output levels to 2004 population assumptions. If the modeler was interested in updating the model to reflect 2014 population numbers, $YA_{a,r}$ would be calibrated to $(1 + 10 * \omega_r)$, where $\omega_r$ is annual population growth rate for each region, and the time step reflects a ten year difference from the base year. This process is repeated for commodity supply, $YC_{c,r}$, and imports, $M_{c,r}$.

The default elasticities in the GTAP data set are usually assumed to represent medium-run behavioral responses. Reaching equilibrium in response to a policy change would be expected to take approximately 5 years, so the updating procedures described above should be calibrated to reflect 5-year time steps.

The FARM model is implemented using the GAMS programming language. The GAMS code for the FARM model is available upon request. The model is represented as a mixed complementary problem (MCP), uniquely pairing each model variable with a single model equation. The result is a square system of nonlinear equations with a unique solution. The model is solved using the PATH solver (Dirkse and Ferris, 1995; Ferris and Munson, 2000).

# Chapter 4

# Global Impact of U.S. Cellulosic Biofuel Production

## 4.1 Introduction

Recent price, demand/supply, and trade movements in global commodity markets have drawn increasing attention to the impact of biofuel production and policy on these markets. At the same time, many nations view domestic biofuel production as a way of improving rural development, increasing energy security, and reducing greenhouse gas emissions. The implications of these national policies has garnered the interest of researchers and policymakers; however, inquiries have tended to focus primarily on the impacts of conventional ethanol production, using coarse grains and oil seeds in the U.S./EU and sugarcane in Brazil. To date, there has been little research on the potential impacts of cellulosic biofuel production.

The implications of diverting corn use to the U.S. ethanol industry have been thoroughly studied in the literature. While most studies simulate different ethanol production scenarios and have differing behavioral assumptions, results are directionally consistent (Gurgel et al., 2007; Hertel et al., 2008; Rosegrant et al., 2008; Hayes et al., 2009; Gehlhar et al., 2010; Timilsina et al., 2010; Chen et al., 2011). These results suggest that there are two important unintended consequences of conventional ethanol production. First, increased ethanol demand for corn increases not only domestic and global corn prices, but also the prices of other major agricultural commodities such as wheat and oil seeds. Second, biofuel production induces changes in domestic and global land cover, primarily from forest and grassland ecosystems to cropland. These land-use changes result in higher terrestrial greenhouse gas emissions (Searchinger et al., 2008; U.S Environmental Protection Agency, 2010; Hertel et al., 2010; Wang et al., 2011).

Both of these unintended consequences result from domestic and global linkages in agriculture and energy markets. In U.S. corn markets, an increase in demand stimulates a supply response whereby farmers increase production either through intensifying non-land inputs on existing corn acreage or by increasing corn acreage. Input intensification increases the costs of production for corn, which is compensated through a higher price. Ethanol demand for corn also induces an acreage response and a share of the increase in corn price is capitalized into higher land rents. The intensification and acreage responses do not just increase the domestic price of corn, but of other important agricultural commodities as well. Higher corn prices induce an increase in demand for other grains as U.S. livestock and poultry producers adjust feed ratios to reflect the change in relative input prices. This substitution response therefore has the effect of increasing non-corn grain prices. The corn-acreage supply response also increases the price of other major agricultural commodities (oilseeds and wheat) as costs of production increase resulting from higher land rents. For a detailed theoretical exposition of these tradeoffs, refer to Feng and Babcock (2010). Strong domestic demand from the ethanol, feed, and processing industries, along with higher domestic commodity prices, has the effect of crowding out U.S. agricultural commodity exports. Because the U.S. is a large supplier to global commodity markets, the reduction in U.S. exports raises global commodity prices. This is the market mechanism involved in the food/fuel tradeoff. Higher commodity prices also induce a long-run supply response among foreign producers, providing incentives to shift non-cropland into production. This is the market mechanism for the land conversion effect.

In general, these market effects are not specific to any particular agricultural commodity (although magnitudes may vary significantly across crops). Introducing cellulosic feedstocks into the agricultural landscape may or may not trigger similar mechanisms. The magnitude of the unintended consequences is determined largely by the relative value of using crop/pastureland for cellulosic biomass production rather than conventional crop production. Advocates of cellulosic biofuels cite the potential to grow dedicated energy crops on marginally-productive land not otherwise suitable for agriculture. However, this is an assumption of future producer behavior and little observable data is available to support or reject this assumption. Using current U.S. biofuel policy to estimate the future size of the cellulosic biofuel industry, we can parameterize economic equilibrium models in order to analyze the potential magnitude of these effects.

The 2007 Energy Independence and Security Act (EISA) mandates a total of 36 billion gallons (ethanol equivalent) of biofuel production through 2022 (U.S. House of Representatives 110th Congress, 2007). The biofuel component of the EISA is commonly referred to at the Renewable Fuel Standard (RFS). As shown in Figure 4.1, the majority of *new* biofuel (16 billion gallons by 2022) is mandated to come from cellulosic biomass.[18] It is often assumed that large scale production of cellulosic biomass will not impact conventional food/feed crops, since they are not a source of food. However, as noted above, impacts on conventional agricultural markets have little relation to the final use of the commodity. If dedicated energy crops compete for crop or pastureland with food/feed commodities, market interactions will create a spillover effect that could result in higher conventional crop prices.

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[18] Cellulosic biofuel refers to the process of transforming lignocellulosic feedstocks (comprised of lignin, cellulose, and hemicellulose) into fuels. This is in contrast to conventional biofuels, which (as defined in EISA) is ethanol derived from corn starch. Cellulosic biofuels require greenhouse gas emissions 60% below gasoline in order to qualify under EISA.

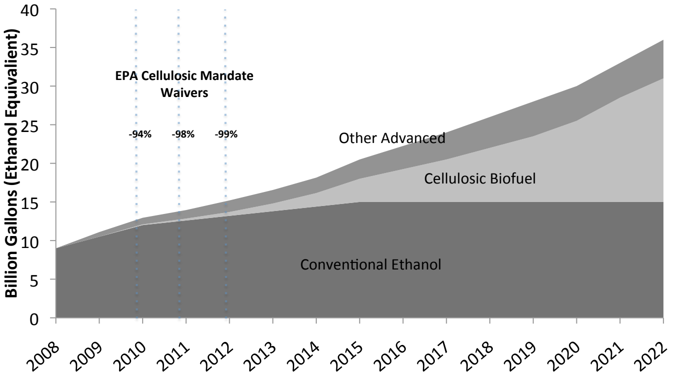

Figure 4.1: U.S. Renewable Fuel Standard 2: Mandates and Waivers

This study uses an applied general equilibrium (AGE) modeling framework in order to provide an analysis of the market mechanisms that potentially cause the two unintended consequences identified above: higher domestic and global prices for conventional agricultural commodities and land-use change. The focus is on the cellulosic biofuel mandate in EISA. Results show that based on feedstock type and land competition assumptions, using cellulosic biomass for biofuel production has the potential to induce considerably large distortions in agricultural commodity markets. The results suggest that the benefits of advanced biofuels from cellulosic biomass may be overstated, as market mechanisms may trigger unintended consequences similar (or greater) to those found with conventional ethanol production.

This paper is organized as follows. Section 4.2 reviews the relevant literature, focusing on preliminary results in the global assessment literature on the potential impact of cellulosic biofuel production on global agricultural markets, and on the production structure of a future cellulosic biofuel industry. The review of the cellulosic biofuel production literature is quantitative in nature and is used as a foundation for constructing new sectors in the assessment model. Section 4.3 describes the model and data, including the methodology for incorporating cellulosic biofuels. Section 4.4 reports the impacts of implementing both the conventional and cellulosic biofuel mandates of the RFS, as well as a sensitivity analysis exploring the effect of varying assumptions on land competition between cellulosic feedstocks and conventional agricultural crops. Section 4.5 includes a discussion of important future research and conclusions.

## 4.2 Literature Review

### 4.2.1 Economic Impacts of Cellulosic Biofuel Production

There have been a limited number of applied general equilibrium (AGE) studies to date exploring the impacts of scaling up cellulosic biofuel production. Campiche et al. (2010) find relatively minor interferences in domestic agricultural markets (focusing on prices, production levels, U.S. exports, and land use) due to increased production of ethanol from corn stover (up to 1.6 billion gallons). This is in line with the notion that stover is a coproduct of corn production for grain and does not directly compete with conventional agriculture commodities for cropland. Several AGE studies focus on the implications of expanding cellulosic biofuel production on domestic and international land use, and the resulting GHG emissions from land use change. Using the MIT Emissions Predictions and Policy Analysis (EPPA) model, Melillo et al. (2009) find that cellulosic biofuel production has the potential to divert significant amounts of pasture and forest land into agricultural production (14-40% and 24-56% respectively) over the next 100 years, both directly, to produce the cellulosic biofuel feedstocks, and indirectly, to make up for traditional agricultural crops displaced by cellulosic feedstock production. They find that cellulosic biofuel production could result in either positive or negative net GHG emissions depending on land conversion assumptions. If land types are reallocated based on exogenously determined land substitution elasticities, conversion from noncropland, such as pasture and forest, to bioenergy feedstock production is limited, resulting in less carbon released from terrestrial ecosystems. The authors use acreage response (to crop price) elasticities of 0.12-0.6 (estimated in Gurgel et al., 2007), which are consistent with econometric estimates elsewhere in the literature (Huang and Khanna, 2010). Under an alternative land allocation approach, which allows land to be converted once it is economically profitable, large tracks of forest and pasture are converted to bioenergy production globally, releasing above and below ground carbon into the atmosphere. Using this method, the authors report a net increase in GHG emissions from a global biofuel expansion. One important limitation of the Melillo et al. study is that it only considers a generic cellulosic feedstock and does not account for the heterogeneous land requirements of various candidate feedstocks.

Taheripour et al. (2011b) simulate the effects of increasing cellulosic biofuel production on land use and GHG emissions using a modified GTAP model. They find that production characteristics of the cellulosic feedstock have an important effect on land use changes. Corn stover, which does not compete directly for agricultural land, induces minimal changes in conventional agricultural commodity markets,[19] while dedicated energy crops, such as switchgrass and miscanthus, have the potential to drive up agricultural land rents. The results imply changes in conventional commodity prices and exports, although these changes are not explicitly reported. The model is also static, and therefore does not account for intertemporal factors that affect agricultural markets, such as increases in energy and agricultural commodity demand resulting from economic development and population growth.

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[19] Other potential environmental impacts from residue removal, such as soil erosion, are not explicitly modeled; although the authors do account for the higher fertilizer application rates necessary to maintain soil quality.

Changes in factor productivity also change over time and potentially affect equilibrium prices and production levels.

The Taheripour et al. study highlights a major issue with research exploring the impact of using dedicated energy crops as cellulosic biofuel feedstocks. Land use change results from AGE analysis, induced by changes in commodity markets, are often driven by assumptions about the land used to grow cellulosic feedstocks, which determines the direct and indirect competition for land with traditional crops. If, for example, the majority of the land used for switchgrass production comes from idled, rather than existing, cropland (often referred to as 'marginal land'), we may expect minimal impacts on conventional agricultural markets. However, growing feedstocks on non-marginal cropland incurs a higher opportunity cost which would be capitalized into higher prices for all commodities. Note that this discussion is relevant to both the food/fuel debate and the discussion on greenhouse gas emissions from land use change.

### 4.2.2 Cellulosic Biofuel Costs of Production

A central hypothesis of this study is that cellulosic feedstocks, grown as inputs into the advanced biofuel industry, interact with world agricultural markets because they potentially compete for land suitable for other agricultural products. Therefore, it is critical to understand the production characteristics of these heterogeneous feedstocks. Extensive commercial production for cellulosic feedstocks does not yet exist; however, numerous agro-economic studies have been conducted to explore the optimal methods for growing, harvesting, storing, and transporting cellulosic feedstocks.

Switchgrass is a perennial grass, native to North America. Once established, switchgrass stands are capable of producing high biomass yields for 10-15 years if properly maintained.

Stand establishment requires aggressive herbicide application to combat weed competition. Poor stand establishment in the first year requires reseeding the following year. This study follows Khanna et al. (2008) and assumes a 25% reseeding rate, which can also be interpreted as a 25% chance of stand establishment failure. After the switchgrass stand is established, fertilizer application is required to optimize yield. Optimal application rates vary based on regional soil characteristics and management practices (Aravindhakshan et al., 2011; Nikièma et al., 2011).

Harvesting practices for switchgrass are similar to hay, and identical harvesting equipment can be used. A single harvest per year, after frost, is optimal for yield and stand maintenance (Perlack and Stokes, 2011). Yield losses are assumed during the storage phase, and represent and important opportunity cost for producers. Estimates of dry biomass lost in the storage phase vary from 20-25% (Jain et al., 2010; Mitchell et al., 2010). Table 4.1 provides an overview of the costs of production for switchgrass based on the literature. Estimates used in this study to construct a representative switchgrass sector are also reported and are calculated as averages across the three reported studies.

Lifetime unit costs are calculated as the net present value over an 11-year stand lifetime at a 4% discount rate (Jain et al., 2010). Costs from Jain et al. (2010) and Duffy (2008) were based on the best agronomic data available on switchgrass production. Perrin et al. (2008) is based on ten farmer production trials in Nebraska, South Dakota, and North Dakota. While the average costs of production in Perrin et al. (2008) are considerably lower than those reported in the other two studies, there was a wide cost range amongst the trial participants ($41.54-$107.05/dry tonne).

Table 4.1: Costs of Production for Switchgrass ($/hectare)

| Study | Jain et al. (2010)[1] | Perrin et al. (2008) | Duffy (2008) | This Study |
|---|---|---|---|---|
| Fertilizer | $151.59 | $40.48 | $166.24 | $119.47 |
| Herbicide | $13.31 | $18.87 | $22.52 | $18.23 |
| Seed | $23.19 | $6.75 | $19.72 | $16.55 |
| Interest | $13.19 | $0.00 | $8.43 | $7.20 |
| Preharvest Machinery | $20.25 | $16.07 | $43.56 | $26.63 |
| Harvesting | $300.25 | $116.98 | $319.56 | $245.60 |
| Land Rent | $632.00 | $165.64 | $232.74 | varies |
| Break-Even Price[2][3] | | | | |
| Not Including Land Rent | | | | |
| $/ha | $521.88 | $199.15 | $580.02 | $433.68 |
| | ($58.39) | ($36.13) | ($58.68) | ($53.47) |
| Including Land Rent | | | | |
| $/ha | $1153.88 | $363.79 | $812.76 | N/A |
| | ($129.10) | ($66.19) | ($82.23) | |
| Yield (tonnes/ha) | 8.94 | 5.51 | 9.88 | 8.11 |

[1] Estimates have been averaged over region and high/low cost scenarios.

[2] Many studies do not include storage and transportation costs and are not reported in this table. This study does assume that these costs are incurred by the farmer and follows estimates from Duffy (2008).

[3] Estimate in $/dry tonne are in parentheses.

This study assumes that storage and transportation are incurred solely by the agricultural producer. Studies have estimated transportation costs to range from \$14-36/dry tonne, while storage costs range from $2-17$/dry ton Perlack and Stokes (2011). This study follows Duffy (2008) and assumes transportation costs of \$14.75/dry tonne (\$120/ha) and \$16.67/dry tonne (\$135/ha) for storage.

Estimates of the break-even prices for switchgrass (per hectare) vary considerably in the literature, driven by yield, input prices, and land rent. This study assumes a break-even price of \$84.89/dry tonne (\$688.46/ha), calculated from the information above. This price excludes land rental payments which are varied in the sensitivity analysis described in Section 4.4.2. Land rent for switchgrass production is an especially important factor to consider, as rental rates reflect the opportunity cost of a given hectare of land and are critical in determining the type of land that switchgrass will displace. Our break-even price is higher than other reported estimates because of the inclusion of transportation and storage costs. Stated preference studies suggest that the break-even prices estimated in the crop budgeting literature could induce producers to convert sizable acreage to dedicated energy crops (Fewell et al., 2011; Jensen et al., 2007). This study assumes a risk-neutral producer and does not take into account potential risk premiums that might be required to switch production from annual to perennial crops (Bocquého and Jacquet, 2010).

Agricultural residue from conventional crop production is an appealing cellulosic biofuel feedstock due to its wide availability and compatibility with existing production practices. Corn stover yield is calculated as

$$y_{\text{stover}} = \rho(1-\pi)(1-\alpha)y_{\text{grain}}$$

where $y_{\text{stover}}$ is corn stover yield, measured in dry tonnes/hectare and $y_{\text{grain}}$ is the grain weight (yield) at harvest, measured in tons/hectare. $\rho$ is the residue to grain ratio, $\pi$ is the moisture content (%) of the grain, and $\alpha$ is the corn stover removal rate. $\pi$ and $\rho$ are assumed to be 15% and 1.0 respectively (Perlack and Stokes, 2011). We can therefore observe that for a given removal rate, stover yields increases linearly over time with grain yields.

Removal rates have been estimated based on USDA sustainability criteria, such as soil maintenance and erosion. The sustainability criteria, in turn, depends on topology, region, soil type, tillage regime, and numerous other factors (Perlack and Stokes, 2011). Obviously sustainable removal rates are going to vary considerably across the United States. In regions suitable for growing corn, estimates vary from 20%-80% (Perlack and Stokes, 2011). A 50% removal rate is assumed for this study, which reflects an average rate in the corn-belt. Assuming a corn grain yield of 155 bushels/acre, this implies a stover yield of 5.36 dry tonnes/ha.

The direct costs of corn stover production can be separated into four distinct categories: nutrient replacement, harvest, storage, and transportation to the refinery. Table 4.2 shows the average costs of production used for this study. When stover is removed from the field there is a resulting loss in nitrogen, phosphorus, and potassium, which must be replaced in order to maintain soil fertility. Harvest costs include the machinery, labor, and fuel required to collect and bail the stover. Storage costs assume that a multi-farm storage facility is used for a large collection radius and includes building costs and labor. Transport costs consist of moving the stover from the field to the storage facility and then from the storage facility to the refinery. Costs include labor, fuel, and truck ownership and maintenance costs. The break-even cost of production is \$65.26/dry tonne (\$275.52/ha). Overviews of the direct

Table 4.2: Costs of Production for Corn Stover

| | Average Rates | Cost ($/ton) |
|---|---|---|
| Nutrient Replacement | | **$14.45** |
| (lbs/ton of residue removed) | | |
| N | 19.3 | $5.06 |
| P | 12.6 | $2.64 |
| K | 48.2 | $6.75 |
| Harvest | | **$21.01** |
| Mowing/Conditioning | - | $3.86 |
| Raking | - | $2.37 |
| Bailing | - | $14.79 |
| Storage | - | **$15.72** |
| Transport | - | **$14.08** |
| Total Costs | | **$65.26** |

costs of corn stover production are provided by National Academy of Sciences (2009) and Perlack and Stokes (2011).

Cellulosic feedstocks are used as inputs in the production of liquid transportation biofuels. Currently there are very few commercial-scale cellulosic biorefineries in the United States, and therefore any costs of production estimates for the industry contain a high degree of uncertainty. The production literature reviewed and presented here on the cellulosic biofuel refining process represents the most current research on the technoeconomic refinery production process. Two types of conversion pathways are considered: biochemical and thermochemical. The biochemical conversion process is similar in nature to conventional ethanol production. Sugars in the biomass are converted into fuel using enzymatic hydrolysis. The process is complicated by the difficulty of separating the cellulose/hemicellulose, which contains fermentable sugars, from lignin, which does not. The enzymes required in this process are much more expensive than in conventional ethanol production. Thermochemical conversion breaks down the biomass using heat, rather than enzymes. The plant material is usually gasified and converted in synthesis gas, which can then be transformed into various fuels.

Table 4.3 shows a breakdown of the production costs from several recent studies for both thermochemical and biochemical conversion pathways. In order to normalize various fuels based on energy content, all values are reported in gallons of gasoline equivalent (denoted hereafter as gge). All thermochemical and biochemical conversion pathways reviewed use a cellulosic feedstock. Interestingly, when averaged across all cellulosic platforms, feedstock costs for advanced biofuels ($1.16/gge) are almost identical to the cost of using corn in conventional refineries ($1.19/gge). As expected, both non-feedstock operating costs and capital costs are significantly higher for cellulosic biofuel refineries than conventional ethanol refineries. Enzymes required in the biochemical conversion process to separate cellulose/hemicellulose and lignin account for a large portion of the non-biomass operating costs. Capital costs for thermochemical refineries are also much higher than biochemical refineries. It is unclear whether a future cellulosic biofuels pathway will follow the thermochemical or biochemical (or both) production process. Both processes are currently uneconomical; however, rising gasoline and corn prices make the industry increasingly competitive. This study creates a hybrid cellulosic refining industry that averages costs and yields across the two conversion processes. The assumed $/gallon (gasoline equivalent) costs are reported in Table 4.3. Table A.2 in appendix A provides further detail on how the operations costs were disaggregated into enzyme, labor, energy, and various other costs required for integration into the AGE model described in Section 4.3.1. The break-even price necessary for cellulosic biofuel production is $3.17/gge, significantly higher than the $2.22/gge break-even price of ethanol.

Table 4.3: Biorefinery Production Costs (\$/gallon of gasoline equivalent)[1,2]

| | Conventional Ethanol | Thermochemical Conversion | | | Biochemical Conversion | | | |
|---|---|---|---|---|---|---|---|---|
| Study | Taheripour et al. 2007 | TTW[3] | Schnepf[4] 2010 | NAS 2009 | TTW | Schnepf 2010 | NAS 2009 | This Study |
| Capital Cost[5] | \$0.34 | \$1.08 | \$0.87 | \$1.21 | \$0.77 | \$0.66 | \$0.51 | \$0.85 |
| Operations Cost | \$0.69 | \$0.47 | \$0.96 | \$1.17 | \$2.04 | \$1.21 | \$1.15 | \$1.17 |
| Feedstock Cost | \$1.19 | \$1.67 | \$1.04 | \$0.55 | \$2.00 | \$1.03 | \$0.64 | \$1.16 |
| Unit Production Cost | \$2.22 | \$3.22 | \$2.87 | \$2.93 | \$4.81 | \$2.90 | \$2.30 | \$3.17 |
| Fuel Yield (gal/dry tonne) | 70.9 | 60.0 | 58.7 | 61.5 | 50.0 | 57.1 | 53.5 | 56.8 |

[1] All estimates are in 2007 dollar

[2] Literature values reported in ethanol energy content have been converted to gasoline energy content. 1 gallon of gasoline = 1.5 gallons of ethanol.

[3] Taheripour et al. (2011b)

[4] CRS estimates are weighted based on the annual fuel output of the biorefinery.

[5] Capital charges per gallon are estimated assuming a 20-year refinery lifetime and 12% interest rate (following Schnepf, 2010). This was applied identically to all studies reviewed in order to compare capital costs for various size refineries.

## 4.3 Methods/Data

### 4.3.1 Future Agricultural Resources Model

In order to capture the interactive effects of the Renewable Fuel Standard across regions and time, the cost of production data reviewed above is integrated into the Future Agricultural Resources Model (FARM), a global dynamic-recursive applied general equilibrium (AGE) model. The model utilizes the GTAP 7 economic data set (Narayanan and Walmsley, 2008) and is expanded to include sectors required to produce conventional ethanol and cellulosic biofuel. FARM is currently under development at the USDA Economic Research Service (ERS). This analysis includes 15 regions, 36 sectors, 38 commodities, and 5 primary factors. Very few modifications are necessary in the underlying model structural equations to incorporate the biofuel module. These modifications occur almost exclusively in altering the social accounting matrix. Modifications of the structural equations for the biofuel module are described below.

FARM is a dynamic recursive model, which allows for multi-period simulations of the RFS, coupled with expected economic development from exogenous population growth, primary energy demand, and changes in factor productivity. The dynamic framework is not utilized in these preliminary results; however, it will be an important component of future sensitivity analysis. Emphasis will be placed on growth in demand for U.S. agricultural exports and projected yield increases in conventional agricultural commodities.

The FARM biofuel module includes four types of biofuels. Three types of conventional ethanol are produced: ethanol from corn grain (in the United States), ethanol from sugar cane (in Brazil), and ethanol from wheat (in the European Union). Dried distiller's grains with solubles (DDGS) are also integrated as a byproduct of the U.S. corn ethanol sector. DDGS are an important protein source and are sold to both the U.S. feed complex, as well as foreign feed markets (primarily China, Mexico, and Canada). Taheripour et al. (2010) show that failing to account for ethanol refinery byproducts can result in a significant overestimation of the global price and land conversion effects of conventional biofuel production. To incorporate conventional biofuels into FARM, we follow Taheripour et al. (2007); Zhou and Kojima (2011). See appendix A for details. Ethanol is converted to gasoline equivalents using a 1.5:1 energy content ratio (Schnepf, 2010).

A cellulosic ethanol sector was constructed based on the production data reviewed above. This sector uses switchgrass and corn stover as intermediate inputs in the conversion process. These cellulosic feedstocks were chosen as model feedstocks in order to generalize the expected impacts of dedicated energy crops (DECs) and agricultural residues. Broadening the analysis to include other DECs, such as miscanthus, and agricultural residues, such as wheat stover, is a future task. Production cost shares are described in Table A.1. Because the conventional corn sector is now capable of producing two commodities, corn and stover, new zero-profit conditions are required. Zero-profit conditions in coproducing sectors are represented by

$$p_a = cy_a(\cdot)$$

$$p_a = \sum_{c=c_1,c_2} \theta_c^{cet}(p_c)^{1-\sigma^{cet}}$$

where $p_a$ and $cy_a$ are the sectoral price and unit cost for industry $a$. This is the standard zero-profit condition. If sector $a$ produces more than one commodity, then the second equation is also required. Here $c_1$ and $c_2$ are the coproducts of sector $a$. $\theta_c^{cet}$ is each commodity's share of the value of total output in sector $a$. $p_c$ is the equilibrium price received for commodity $c$.

$\sigma^{cet}$ is the constant elasticity of transformation parameter describing how sector $a$ producers respond to changes in commodity (output) prices. If the two commodities are produced in fixed proportions, $\sigma^{cet} = 0$. This condition is analogous to the situation where an industry produces one primary product and one byproduct. Output value shares are maintained, and the industry does not change its production process if the price of the byproduct relative to the primary product changes (or vice versa). The $\sigma^{cet} = 0$ assumption is maintained for both the corn stover and conventional ethanol (with DDGS) industries.

Compared to the conventional ethanol refining sector, the cellulosic biofuel refining sector is somewhat more difficult to represent with certainty as there are no commercial facilities in operation and proposed pilot and demonstration refineries use a wide variety of proprietary technologies. These issues are addressed by creating a 'representative' cellulosic biofuel sector based on techno-economic studies in the literature. As noted in Section 4.2.2 a hybrid bio/thermochemical conversion process is modeled. Alternative approaches are described in Campiche et al. (2010); Taheripour et al. (2011b). Production levels in this sector are very small in the base year and expand in model simulations of the Renewable Fuel Standard. Table A.3 in Appendix A shows the base year production assumptions for the all new industries.

Both conventional ethanol and cellulosic biofuels are modeled as intermediate inputs into the refined petroleum sector, which is then directly consumed as transportation fuel by households and firms. Absent any subsidies or production mandates, gasoline blenders choose the lowest cost fuel option. Demand for conventional ethanol is largely driven by the price of crude oil, although blending levels are restricted to 10% in a large percentage of the current vehicle fleet.[20] Cellulosic biofuel is assumed to be a substitute for both ethanol and crude oil, and can be blended at any level as its chemical properties are assumed to be identical to gasoline. See Figure A.1 in Appendix A for the production nesting structure used in this analysis, as well as key structural equations.

The land resource in FARM uses the GTAP land-use data set (Monfreda et al., 2009), which distributes crop production into 18 distinct categories, termed 'agro-ecological zones' (AEZ). The "value of production" flow for land, in the original database, are therefore disaggregated in order to model land heterogeneity. Within a given AEZ, land is allocated based on constant elasticity of transformation parameters that is identical for each land-using sector. This approach is documented in Hertel (1998).

Land cover data compatible with the GTAP data base is also available, and allows for acreage and yield to be factored into the analysis. The land cover data is not used in this study but is will be an important addition for future work, by allowing for acreage constraints and endogenous yield determination.

Switchgrass production is not included in the original GTAP land use database. To resolve this, small amounts of land are split from the wheat sector in the base year. This allows for land resources to be diverted to switchgrass in the model scenarios described below. This study assumes that in the first phase of the U.S. cellulosic biofuel industry, switchgrass can compete with any coarse grain or oilseed crop (similar to wheat). Land shares across AEZs for switchgrass in the base year are assumed to be identical to wheat. The implicit price/hectare for land used for switchgrass (which determines the importance of

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[20] The U.S. Environmental Protection Agency has approved higher blending levels, up to 15%, for light-duty vehicle manufactured after 2001; however, the new rule will take time to implement at a large scale due to additional requirements for interested fuel manufacturers.

land as a primary factor) is assumed to be equal to wheat. This assumption will be relaxed in Section 4.4.2.

Two important sources of cellulosic feedstock heterogeneity have therefore been introduced into the AGE framework. The first is heterogeneity in land requirements *between* cellulosic feedstocks. Corn stover is assumed to not require additional land, whereas switchgrass does. Second, heterogeneity in land suitability for agricultural production allows for testing of the assumptions regarding the *type* of land used for switchgrass production, and therefore, competition with other conventional agricultural commodities.

### 4.3.2 Policy Scenarios

Conventional and cellulosic biofuel production levels, as mandated by RFS, are simulated by exogenously increasing the intermediate demand for these fuels in the refined petroleum sector. The refined petroleum sector (which produces usable transportation fuel) is the primary consumer of biofuels in the United States. The intermediate demand function is increased as follows. For production sector $a$ (in this case, refined petroleum products), the unit cost function for a two-nest CES production function[21] is given by:

$$c^y_a(\cdot) = \left[ \sum_c \theta^i_{c,a} (c^i_{c,a})^{1-\sigma^y}) + \sum_f \theta^{\mathrm{f}}_{f,a} (c^{\mathrm{f}}_{f,a})^{1-\sigma^y} \right]^{\frac{1}{1-\sigma^y}} \tag{4.1}$$

Where $a, c$ and $f$ index economic sectors, commodities, and primary factors respectively. $c^y(\cdot)$, $c^i(\cdot)$ and $c^f(\cdot)$ are the unit cost functions for total output, intermediate inputs and primary factors respectively. $\theta^{i,\mathrm{f}}$are the base year value shares for intermediate inputs and

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[21] This simplified cost function describes a nesting structure where firms choose separately between an intermediate inputs and primary factor inputs. The full nesting structure used for this analysis is described in Appendix A.

primary factors. $\sigma^y$ is the Allen-Uzawa elasticity of substitution between primary factors and intermediate inputs.

Intermediate input demand from sector $a$ for commodity $c$ is given by:

$$q^{\mathrm{i}}_{c,a} = \bar{q}^{\mathrm{i}}_{c,a}\left(\frac{1}{\lambda_{c,a}}\right)\left(\frac{\bar{p}^{\mathrm{i}}_{c} * c^{\mathrm{i}}_{c,a}}{p^{\mathrm{i}}_{c}}\right)^{\sigma^{\mathrm{d}}}\left(\frac{c^{y}_{a}}{c^{\mathrm{i}}_{c,a}}\right)^{\sigma^{y}} \tag{4.2}$$

Where $q^{\mathrm{i}}$ and $p^{\mathrm{i}}$ are the demand and equilibrium price for commodity $c$ used in the production process for sector $a$'s product. Base year values are denoted using accent bars. $\sigma^{\mathrm{d}}$ is the elasticity of substitution between between intermediate inputs and $\lambda$ is the exogenous scaling parameter for commodity $c$ used in sector $a$.

In order to implement the 2022 RFS mandates for each individual type biofuel, $\lambda$ can be set to reflect changes in quantities from the model's base year values. Table 4.4 shows the scaling factors (shown as $\frac{1}{\lambda}$) for each type of biofuel as a function of the mandated quantity, as well as the implied acreage required to grow the cellulosic feedstocks. Four scenarios are established using this approach. First, we set a baseline scenario expected changes in regional population growth and primary energy demand. Next three separate biofuel mandates are imposed, all at 2022 volumes[22]:

- 10 billion gge of conventional ethanol (using corn)
- 10.7 billion gge of advanced biofuel (using switchgrass)
- 10.7 billion gge of advanced biofuel (using corn stover)

Unless otherwise noted, the results below are all presented at differences from the baseline scenario.

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[22] Volumetric mandates are expressed in gallons of gasoline equivalents (gge) to accounts for difference in energy content between ethanol and biogasoline.

Table 4.4: Cellulosic Biofuel Mandates and Feedstock Acreage Requirements

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RFS Mandated Quantities (bgge) | | | | | | | | | | | | |
| Conventional Ethanol | 8.4 | 8.8 | 9.2 | 9.6 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Cellulosic Biofuel | 0.2 | 0.3 | 0.7 | 1.2 | 2.0 | 2.8 | 3.7 | 4.7 | 5.7 | 7.0 | 9.0 | 10.7 |
| Intermediate Demand Scaling Factors ($\frac{1}{\lambda}$) | | | | | | | | | | | | |
| Conventional Ethanol | 2.7 | 2.9 | 3.1 | 3.2 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 |
| Cellulosic Biofuel | 1.5 | 4.0 | 9.0 | 16.4 | 28.9 | 41.3 | 53.7 | 68.7 | 83.6 | 103.5 | 133.3 | 158.2 |
| Cellulosic Biomass Acreage Requirements (millions of hectares)[1] | | | | | | | | | | | | |
| Switchgrass | 0.36 | 0.72 | 1.44 | 2.54 | 4.34 | 6.16 | 7.96 | 10.14 | 12.3 | 15.2 | 19.54 | 23.16 |
| Corn Stover | 0.54 | 1.1 | 2.18 | 3.84 | 6.56 | 9.3 | 12.04 | 15.32 | 18.62 | 23 | 29.56 | 35.04 |

[1] Total land required to fulfill the mandate using *either* corn stover or switchgrass

## 4.4 Results

### 4.4.1 Global Impacts of Implementing RFS Production Mandates

The results below highlight the global impacts of the three biofuel scenarios identified in Section 4.3.2. In order to highlight the unintended consequences of the mandates, emphasis is placed on several particular metrics of concern: Bilateral trade, regional changes in cropland allocation, and representative household consumption.

As seen in Table 4.5 global trade patterns are altered under both the conventional ethanol and advanced biofuel (from switchgrass) mandates. Both U.S. corn and wheat exports increase in the baseline scenario, yet fall considerably (relative to the baseline) after the policies are implemented. Other regions of the world increase agricultural production and exports, due to a rise in global commodity prices, but the total production and trade levels in these sectors decrease overall. Interestingly, if the cellulosic mandate is fulfilled using agricultural residues, such as corn stover, there is almost no effect on international agricultural markets. This stems from the fact that agricultural residues do not command a land rental payment above their coproduct's rental rate.

Table 4.6 shows predicted acreage changes for various regions and agricultural commodities. The indirect land use change (iLUC) effect noted elsewhere in the literature is present in these results as well (Searchinger et al., 2008; Melillo et al., 2009; Wang et al., 2011). As expected, land allocation in the U.S. declines for crops competing with the bioenergy feedstock, although total land use in agriculture increases. As world agricultural commodity prices rise (result not shown), land allocation outside the U.S. tends to increase overall across most crop categories. This effect is much more dramatic under the advanced biofuel mandate

Table 4.5: Bilateral Trade Flows for Corn and Wheat: Impact of Bioenergy Policy on Trade Volumes (million$US). Results for the four bioenergy scenarios are shown as differences in total value from the baseline

| | Corn | | | | | Wheat | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Exp./Imp. Ctry | WestEU | China | MENA/SSA | ROW | **Total** | WestEU | China | MENA/SSA | ROW | **Total** |
| **Baseline** | | | | | | | | | | |
| USA | -12.5 | 49.5 | 49.7 | 299.0 | **385.7** | -68.9 | 49.3 | -0.2 | 169.6 | **149.7** |
| West EU | 228.9 | 0.3 | 23.6 | 57.2 | **310.0** | 400.2 | 10.3 | 453.0 | 71.9 | **935.4** |
| Brazil | -20.6 | 0.0 | 7.8 | 17.3 | **4.5** | -3.2 | 0.0 | -1.4 | -3.5 | **-8.1** |
| ROW | -39.8 | 52.9 | 216.8 | 173.0 | **402.9** | -80.2 | 154.6 | 183.9 | 702.4 | **960.7** |
| **Conventional Ethanol Mandate** | | | | | | | | | | |
| USA | -12.1 | -42.8 | -83.6 | -225.5 | **-364** | -9.9 | -15.6 | -58.0 | -58.2 | **-141.7** |
| West EU | 8.5 | 0.1 | 2.8 | 11.1 | **22.5** | 8.3 | 0.5 | 12.4 | 1.8 | **23.0** |
| Brazil | -0.1 | 0.0 | 5.3 | 11.3 | **16.5** | 0.0 | 0.0 | 0.4 | 0.1 | **0.5** |
| ROW | -0.8 | 17.5 | 40.5 | 108.5 | **165.7** | -1.5 | 9.9 | 11.2 | 40.1 | **59.7** |
| **Advanced Biofuel-Switchgrass** | | | | | | | | | | |
| USA | -46.8 | -187.0 | -335.5 | -1011.9 | **-1581** | -173.5 | -345.2 | -1072.6 | -1271.4 | **-2863** |
| West EU | 55.0 | 0.4 | 16.3 | 65.2 | **136.8** | 174.5 | 14.6 | 353.8 | 45.0 | **587.9** |
| Brazil | -4.6 | 0.0 | 21.9 | 50.7 | **68.0** | -1.0 | 0.0 | 13.8 | -0.2 | **12.6** |
| ROW | -13.4 | 83.6 | 172.4 | 546.0 | **788.7** | -58.5 | 228.5 | 250.3 | 988.0 | **1408** |
| **Advanced Biofuel-Corn Stover** | | | | | | | | | | |
| USA | 0.0 | -0.1 | -0.7 | -0.9 | **-1.7** | -0.8 | -1.4 | -6.9 | -5.8 | **-14.9** |
| West EU | -0.2 | 0.0 | -0.1 | -0.1 | **-0.3** | 0.3 | 0.0 | -0.9 | 0.0 | **-0.6** |
| Brazil | 0.0 | 0.0 | -0.1 | 0.0 | **-0.1** | 0.0 | 0.0 | -0.1 | 0.0 | **-0.1** |
| ROW | 0.2 | 0.1 | -0.4 | 0.3 | **0.2** | 0.4 | 1.1 | 0.3 | 4.0 | **5.9** |

if switchgrass is used. iLUC effects are essentially non-existent if using an agricultural residue feedstock, such as corn stover.

Tables 4.7 reports changes in household expenditure by region and a decomposition of these expenditures into food and energy expenditures. While overall spending (relative to the baseline expenditures) tends to increase by a small amount (relative to total macroeconomic consumption levels), when food products are separated out, we observe higher expenditures. This is especially apparent in the advanced biofuel from switchgrass scenario. For food importing regions, such as the Middle East and North Africa, these higher expenditures on food products are likely allocated primarily to imports and therefore presents an adverse impact on regional households.

Table 4.8 further decomposes regional household expenditures into a quantity index, showing the percentage change in the quantity consumed relative to the baseline. These values are adjusted by the commodity's share of total household consumption. Results for processed food products show that under the conventional ethanol and advanced biofuel from corn stover scenarios total food consumption in the economy does not change significantly relative to the baseline in most regions, despite the increase in household expenditures on food products. Combined with the household expenditure results above, this suggests that large price increases, rather than increased consumption, are responsible for the increases in household expenditures on food products. This result confirms the food/fuel tradeoff which can be especially harmful in low-income food-importing open economies. Interestingly, the tradeoff is much more apparent under an advanced biofuel from switchgrass policy than either of the other two policies considered. Under this policy, total household consumption of food products actually decreases in many nations quite considerably. The nations that

Table 4.6: Global Acreage Effects of U.S. Bioenergy Policy: Total and percentage change in hectares from 2004.

| | USA | EU | China | Brazil | ROW |
|---|---|---|---|---|---|
| **Conventional Ethanol** | | | | | |
| Corn | 3,004,153 | 9,924 | 199,566 | 33,767 | 186,547 |
| | 10.1 | 0.1 | 0.8 | 0.3 | 0.3 |
| Wheat | -463,698 | 3,296 | 12,330 | 1,273 | 103,333 |
| | -2.3 | 0.0 | 0.1 | 0.0 | 0.1 |
| Other Coarse Grains | -55,300 | -3,822 | 4,525 | 31 | -30,106 |
| | -1.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| Oil Seeds | -499,632 | 6,278 | 51,577 | 25,788 | 81,052 |
| | -1.3 | 0.1 | 0.2 | 0.1 | 0.1 |
| Sugar Cane | -6,977 | -987 | -519 | -4,501 | -8,197 |
| | -0.8 | 0.0 | 0.0 | -0.1 | -0.1 |
| Other Crops | -78,582 | -6,301 | -11,723 | -8,190 | -45,435 |
| | -1.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Advanced Biofuel- Switchgrass** | | | | | |
| Corn | -7,435,385 | -37,605 | 940,382 | -67,066 | 241,036 |
| | -25.0 | -0.4 | 3.7 | -0.5 | 0.3 |
| Wheat | -9,278,021 | 245,899 | 351,626 | 34,531 | 2,367,349 |
| | -45.9 | 0.9 | 1.6 | 1.2 | 1.6 |
| Other Coarse Grains | -1,347,996 | -115,792 | 81,665 | 11,454 | -96,415 |
| | -24.9 | -0.5 | 2.1 | 0.8 | -0.1 |
| Oil Seeds | -11,466,340 | 181,471 | 1,550,966 | 811,385 | 2,551,431 |
| | -30.9 | 1.9 | 5.3 | 3.5 | 2.0 |
| Sugar Cane | -164,631 | -27,728 | -8,900 | -104,797 | -130,893 |
| | -18.1 | -1.2 | -0.6 | -1.9 | -0.8 |
| Other Crops | -1,737,621 | -138,141 | -157,985 | -166,245 | -438,830 |
| | -31.8 | -0.7 | -0.2 | -1.0 | -0.1 |
| **Advanced Biofuel- Corn Stover** | | | | | |
| Corn | 51,269 | 41 | 266 | 192 | -2,937 |
| | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| Wheat | -41,556 | 848 | 1,120 | -35 | 19,768 |
| | -0.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| Other Coarse Grains | 639 | 233 | 140 | 34 | -6,844 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Oil Seeds | 10,381 | -76 | -2,026 | -1,342 | 2,665 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sugar Cane | 112 | 50 | 7 | 516 | -53 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Other Crops | 64 | -429 | 77 | 206 | -3,306 |
| | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table 4.7: Difference in Regional Household Expenditures from Baseline(million $US )

| | **Conventional Ethanol** | | | **Advanced Biofuel Switchgrass** | | | **Advanced Biofuel Corn Stover** | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | Energy | Food | Total | Energy | Food | Total | Energy | Food |
| USA | 0 | 869 | 90 | -275 | 30,770 | 5,220 | -274 | 310 | -47 |
| WestEU | 4,766 | 198 | 577 | 132,860 | 7,324 | 16,135 | 1,562 | 51 | 182 |
| EastEU | 287 | 24 | 66 | 6,769 | 652 | 1,584 | 81 | 6 | 18 |
| OthOECD | 783 | 32 | 113 | 33,287 | 1,537 | 4,567 | 107 | 3 | 13 |
| China | 701 | 25 | 170 | 19,818 | 856 | 4,725 | 234 | 7 | 52 |
| India | 394 | 25 | 171 | 8,842 | 786 | 3,720 | 125 | 5 | 54 |
| Indonesia | 94 | 3 | 27 | 3,713 | 212 | 1,024 | 16 | 0 | 4 |
| Japan | 1,540 | 38 | 208 | 42,776 | 1,548 | 5,452 | 570 | 10 | 67 |
| OthAsia | 631 | 26 | 146 | 17,665 | 1,021 | 3,978 | 225 | 7 | 47 |
| MENA | -487 | -53 | -104 | 13,560 | 1,133 | 3,474 | -405 | -40 | -96 |
| SSA | -37 | -5 | -8 | 6,818 | 280 | 2,684 | -129 | -7 | -47 |
| Brazil | 350 | 29 | 58 | 11,391 | 1,077 | 1,857 | 89 | 6 | 14 |
| OthLA | 28 | 0 | 33 | 19,928 | 1,105 | 3,237 | -244 | -12 | -33 |
| Russia | -3 | -3 | 2 | 10,343 | 1,262 | 2,720 | -62 | -9 | -16 |
| OthREF | 77 | 12 | 26 | 3,781 | 670 | 1,202 | 8 | 1 | 3 |

experience an increase in food product consumption are primarily agricultural commodity exporters who are benefiting, through higher incomes, from the increase in global agricultural commodity prices.

Several general observations may be made from these results. First, producing renewable transportation fuels from agricultural biomass sources can significantly distort global agricultural and energy commodity markets. This is not determined by whether the feedstock is itself a food crop, but whether or not it competes for land with food crops. Fulfilling the advanced biofuel mandate with a crop such as switchgrass would require approximately 23.2 million hectares of land in the U.S. If pulled from the existing agricultural land base, this would require allocating almost a 10% of the U.S.'s 2007 harvested land resources to biofuel production. These potential distortions impact bilateral trade, domestic production, and land allocation globally. The latter effect is not insignificant and depending on where

Table 4.8: Household Quantity Consumption Index: Percentage change in household consumption by commodity (relative to baseline)

| | US | Jpn | WEU/EEU | OECD | Rus | ROW | Chn | India | Indon. | ROA | MENA | SSA | Bra | LA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Conventional Ethanol** | | | | | | | | | | | | | | |
| Gasoline | -0.05 | 0.00 | 0.02/0.01 | 0.02 | 0.02 | 0.02 | 0.01 | 0.02 | 0.01 | 0.01 | 0.03 | 0.02 | 0.02 | 0.06 |
| Processed Food Products | 0.00 | 0.00 | 0.00/0.00 | 0.00 | 0.00 | -0.02 | 0.00 | 0.00 | -0.02 | -0.01 | 0.00 | 0.00 | -0.01 | 0.00 |
| **Advanced Biofuel-Switchgrass** | | | | | | | | | | | | | | |
| Gasoline | -1.11 | 0.05 | 0.43/0.24 | 0.61 | 0.42 | 0.36 | 0.11 | 0.21 | 0.10 | 0.17 | 0.45 | 0.23 | 0.61 | 1.27 |
| Processed Food Products | -0.30 | -0.02 | 0.03/0.00 | 0.03 | 0.05 | 0.02 | -0.03 | 0.05 | -0.08 | -0.05 | -0.03 | 0.02 | -0.10 | -0.07 |
| **Advanced Biofuel-Corn Stover** | | | | | | | | | | | | | | |
| Gasoline | -0.03 | 0.00 | 0.01/0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.04 |
| Processed Food Products | 0.00 | 0.00 | 0.0/0.0 | 0.00 | 0.00 | -0.02 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

new land resources are pulled from, could potentially mitigate a portion the greenhouse gas benefit obtained from producing renewable transportation fuels.

We also observe a considerable "rebound effect" in global transportation fuel markets (Hochman et al., 2010). Higher transportation fuel prices in the U.S. resulting from the use of higher cost biofuel additives depresses U.S. demand for petroleum. This in turn depresses global fuel prices and increases the quantity of fuel demanded in other nations. Our results, shown in Table 4.8, suggest the total fuel consumed by households increases in every region outside of the U.S. as result of lower world gasoline prices (induced by U.S. biofuel production). The rebound effect is strongest for switchgrass-derived advanced biofuel. Conventional ethanol and stover-derived advanced biofuels show much smaller, but still observable rebound effects in global transportation fuel markets. As with the iLUC effect, the rebound effect can be expected to offset some of the greenhouse gas emissions reductions of a bioenergy policy.

### 4.4.2 Land-Use Efficiency of Cellulosic Feedstocks

The results presented above suggest that the unintended consequences of advanced biofuel production are driven primarily by the land-use efficiency of the agricultural feedstocks. Isolating the effects of corn stover vs. switchgrass use highlights the fact that biofuel feedstocks with a higher opportunity cost of land will induce larger impacts. This suggests that the fairly dramatic economic impacts of large scale switchgrass production could vary considerably depending upon assumptions regarding land use in general, and, in particular, the opportunity cost of that land.

Previous studies have shown that switchgrass is a candidate cellulosic feedstock for large-scale production in many regions of the United States (Walsh et al., 2003; Khanna et al., 2011). It is very possible that switchgrass could displace land of high or low quality (in terms of agricultural production). As shown in Figure 4.2, switchgrass grown in the most productive regions of the corn-belt would have an implicit land value equivalent to the net economic profit of a corn-soy or continuous corn rotation (or other predominant production systems). Switchgrass grown in the Northern or Southern Plains regions would likely compete with livestock production for grassland. The value of land in these regions would be much lower, perhaps equal to the net economic profit from hay production. Finally, switchgrass grown in the southeast United States is likely to compete directly with a broader array of agricultural commodities, although cropland values in this region are generally much lower than the corn-belt. One assumption that the model may be highly sensitivity to is the inherent productivity of land where switchgrass is being grown.

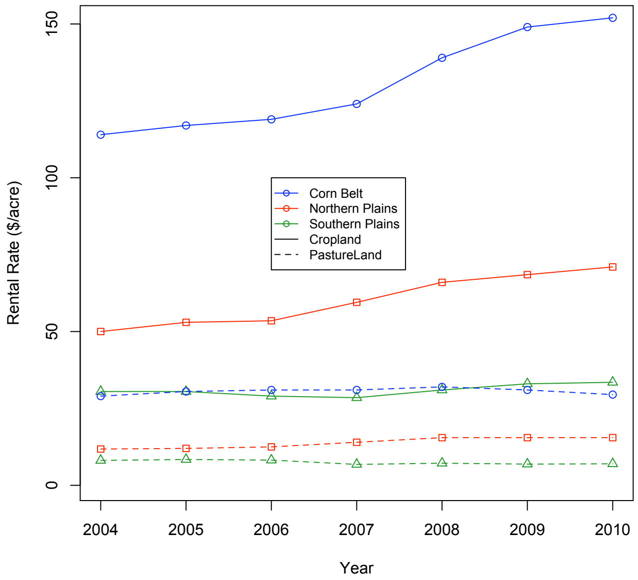


Figure 4.2: Regional Land Rental Rates in the U.S.($/acre) Source: National Agricultural Statistics Service (2009)

It is straight forward to use a scalar on land productivity to examine the importance of our initial assumptions regarding the productivity of where switchgrass is grown. Adjusting this scaling parameter reflects the ability to alleviate the switchgrass land constraint as follows. Using the cost function described in equation 4.1, the primary factor input demand function for any sector $a$ is given by:

$$q^{\mathrm{f}}_{f,a} = \bar{q}^{\mathrm{f}}_{f,a} \left( \frac{1}{\phi_{f,a}} \right) \left( \frac{\bar{p}^{\mathrm{f}}_{f,a} * c^{\mathrm{f}}_{a}}{p^{\mathrm{f}}_{f,a}} \right)^{\sigma^{\mathrm{f}}} \left( \frac{c^{y}_{a}}{c^{\mathrm{f}}_{a}} \right)^{\sigma^{y}} \tag{4.3}$$

Where $q^{\mathrm{f}}$ and $p^{\mathrm{f}}$ are the demand and equilibrium price (or rental rate) for primary factor $f$ (in this case, land) in sector $a$. Base year values are denoted using accent bars. $\sigma^{\mathrm{f}}$ is the elasticity of substitution between primary factors and $\phi$ is the exogenous scaling parameter for primary factor $f$ in sector $a$. Higher values of $\phi$ imply that as land in the U.S. is moved into switchgrass production, the opportunity cost of its alternate uses declines. This acts as a proxy for improvements in switchgrass yields or the availability of additional land not currently in production. Figure 4.3 shows the impact of varying $\phi_{\mathrm{land}}$ for the switchgrass sector on domestic and international land allocations to several key agricultural commodities. These land use changes are directly connected to the household expenditure results presented in Section 4.4.1 and based on a reduced production mandate of 1 billion gallons (gasoline equivalent) of advanced biofuel. The reduced mandate is used in order to more realistically reflect the marginal changes in the switchgrass sector over the next decade, since it is unlikely that the full mandate will be met using perennial grasses such as switchgrass. Clearly, as the cost of displacing alternative agricultural commodities decreases (moving along the x-axis), distortions in both domestic and international commodity markets decline.

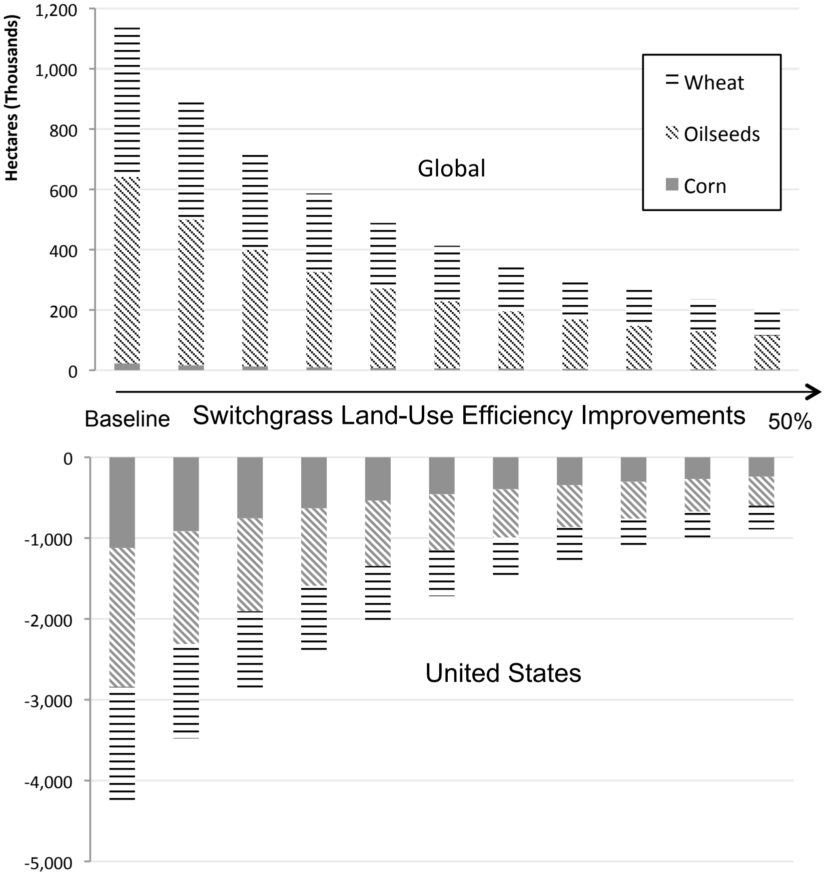


Figure 4.3: Effects of Switchgrass Land-Use Efficiency on Domestic and Global Land Use Change

The baseline model is based on our best estimate of land productivity, where $\phi$ is equal to 1. An increase in $\phi$ requires investments by the private or public sectors in biotechnologies or increased land availability. Incentives to invest in yield improving technologies, for example, would reduce the land requirements for switchgrass. Another alternative would be to allow for switchgrass production on productive agricultural land not currently used for other commodities, such as land enrolled in the Conservation Reserve Program.

Finally, a policy interpretation can be connected to changes in $\phi$. The model already addresses one policy objective, the biofuel mandate. As previously discussed, another policy goal might be to produce switchgrass on marginal lands, which is accomplished by increasing $\phi$. The level of productivity dictates the potential tradeoffs between two policy objectives as shown in Figure 4.4. The first objective, the biofuel mandate, is represented on the vertical axis and the second objective, marginal lands, is represented on the horizontal axis. The mandate is expressed as a percent increase in the quantity of biofuels produced and marginal lands is an index of the opportunity cost of land placed into switchgrass, where higher values imply more switchgrass being planted on marginal lands. The tradeoffs for accomplishing both objectives can be represented by a ray from the origin (the linear case is shown for simplicity but is not a necessary assumption). If $\phi$ equaled $\phi_1$, a mandate of M could be reached with a level of marginal lands equal to $L_1$. If $\phi$ equaled $\phi_3$, the mandate goal, M, could not be attained. If feedstock productivity were to improve, perhaps due to advances in biotechnology, $\phi$ would increase to $\phi_2$ and the mandate could be achieved using a higher quantity of marginal land, $L_2$. This productivity improvement would reduce the burden on other agricultural crops as well as the pecuniary effects identified above. However, we cannot determine where $\phi$ is based on our current modeling effort. Therefore, we cannot determine if it is even possible to achieve the mandate, while also trying to fulfill a second policy objective of pushing production to marginal lands. However, we can show that it is important in the future to determine where $\phi$ is so that realistic policy objectives are chosen, including tradeoffs between the mandate and where switchgrass is produced, and how $\phi$ is changing or could be changed with policies to invest in biotechnology or land availability.

## 4.5 Conclusion

Incorporating the mandated expansion of cellulosic biofuel production into global biofuel impact assessments is essential for evaluating the stated objectives and consequences of

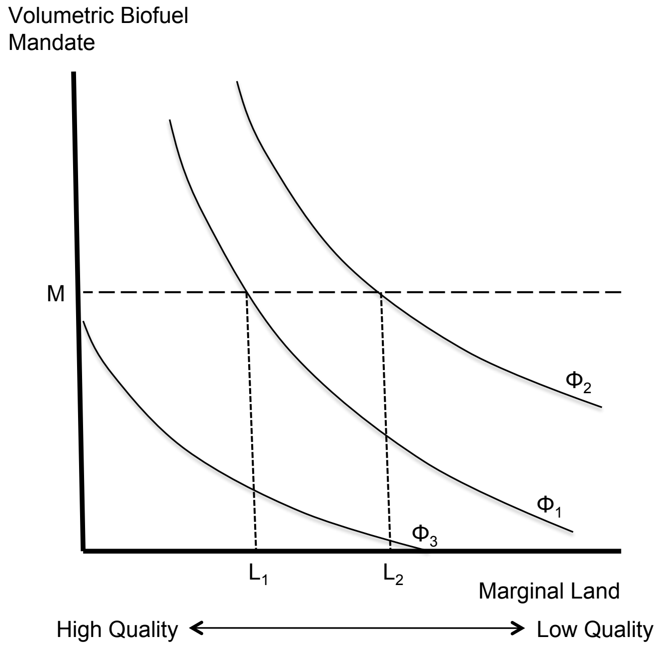


Figure 4.4: Tradeoffs in Meeting the Renewable Fuel Standard Using Marginal Lands

U.S. bioenergy policy. This study uses an analysis of two candidate cellulosic feedstocks, switchgrass and corn stover, to provide insights into the possible domestic and international economic impacts of the U.S. biofuel program. Several interesting conclusions are apparent, but the key finding is that negative impacts are lowest for marginal lands, where "marginal" implies land where there is the least competition from traditionally grown crops. Impacts are largely determined by the amount of new land area required to produce cellulosic biomass. In the case of corn stover, agricultural residues can be harvested from existing cropland used for the production of conventional commodities and therefore do not induce additional competition for land. On the other hand, dedicated energy crops, such as switchgrass, do require additional land resources and therefore increase land competition. Inelastic demand for these displaced commodities causes pressure to expand the cropland margin, both domestically and internationally. The result is indirect land-use change. To the extent that overall production of agricultural commodities declines, global markets respond through higher prices. Therefore, there is a tradeoff between increasing commodity prices and externalities that arise from cropland expansion.

While previous studies have shown that these tradeoffs are sensitive to assumptions regarding the relationship between crop price and yield, the elasticity of land supply, and the availability of idled cropland, this study identifies a fourth important factor: systemic yield uncertainty for dedicated energy crops. There is simply too little experience with dedicated energy crops to accurately gauge their potential yield. Higher yield assumptions imply lower acreage requirements necessary for meeting the cellulosic biofuel mandate. Therefore high-yielding energy crops have a lower impact on the land margin. As the cellulosic biomass industry expands, more precise yield estimates will allow researchers to better gauge the impact of bioenergy feedstock production on other agricultural commodity markets.

The results presented in this analysis are not meant to be predictive. Instead, they are meant to highlight tradeoffs that will arise as a result of U.S. bioenergy production and policy. Land is a scarce economic resource and increasing demand for biomass from the energy sector can be expected to place additional economic pressure on other commodities that require land. The Renewable Fuel Standard provides very few incentives to allocate land for bioenergy production in a way that minimizes adverse effects that arise due to land scarcity. Refinements in the RFS regulations could provide incentives for the biofuel industry to use renewable feedstocks that either do not compete for agricultural land or use such land as efficiently as possible. One policy option for is to steer production to lower yielding land such as, for example, land in the Conservation Reserve Program, where appropriate. Using land more efficiently for feedstock production could be aided by investments in research targeted toward increasing yields in energy feedstocks. Based on results here, the impacts of the RFS could be greatly reduced with appropriate companion policy.

# Chapter 5

# Policy-Induced Competition in Cellulosic Biomass Markets

## 5.1 Introduction

The focus of Chapter 4 was on renewable transportation fuel production pathways, where renewable biomass would displace petroleum in the transportation fuel sector. A growing body of evidence suggests that bioenergy from advanced feedstocks, such as agricultural residue and dedicated energy crops, can reduce overall GHG emissions relative to both corn ethanol and fossil fuel consumption (Farrell et al., 2006; Wang et al., 2011; Davis et al., 2011). This would appear to be consistent with claims that policy incentives for biofuel production are justified, at least in part, by GHG reduction benefits. However, biomass conversion to transportation fuel may not be the most efficient, least-cost method of reducing greenhouse gas emissions. For example, several recent life-cycle assessment studies have suggested that biomass conversion to electricity, rather than transportation fuels, may be a more efficient use of productive land resources (Campbell et al., 2009; Lemoine et al., 2010). Several economic analyses have reached similar conclusions (Schneider and McCarl, 2003; Reilly and Paltsev, 2007; Rose and Mccarl, 2010).

Yet, bioenergy policy in the U.S. and many other nations strongly favors renewable transportation fuel production pathways, often through minimum consumption mandates. At the same time, market-based greenhouse gas reduction policies are currently in place or being considered around the world. These market-based GHG policies are largely agnostic in terms of technology pathways, while renewable transportation fuels are not. Limited attention has been given to both the efficiency of these policies in terms of the incentives created to use scarce land resources for bioenergy production, as well as potential policy interaction effects driven by competition for renewable biomass. This is likely to become increasingly relevant as nations pursue dual policies for reducing greenhouse gas emissions and increasing renewable transportation fuel consumption. For example, the European Union has already established both a cap-and-trade program as well as a 10% consumption target for biofuels in transportation fuel. In the United States, a Renewable Fuel Standard sets minimum consumption mandates for transportation fuel derived from cellulosic biomass, while the debate continues over whether to implement cap-and-trade or carbon tax programs for reducing GHG emissions. The issue is also relevant for developing nations such as China, India, Indonesia, Malaysia, and Thailand, all of which ahave mandatory biofuel blending requirements (see Sorda et al., 2010, for a detailed summary of international biofuel policies).

The objective of this study is to explore how renewable transportation fuel mandates interact with economy-wide market-based GHG mitigation policy. The focus is on policy-induced competition between the transportation and electricity sectors for cellulosic biomass, such as agricultural residues and dedicated energy crops. Using the FARM general equilibrium model I show that simultaneously implementing a GHG cap-and-trade policy and the cellulosic biofuel consumption mandate increases the domestic compliance costs for each policy. This is due to competition for cellulosic biomass in domestic markets. The analysis is extended by considering both the domestic and international welfare effects of this policy interaction. Welfare impacts are found to be determined by terms of trade adjustments, based largely on a region's import and expert share of global energy and agricultural commodity markets.

This study contributes to both the bioenergy and GHG-mitigation policy literature in several ways. First, it adds to the growing body of literature suggesting that biomass for electricity production appears to be a more efficient GHG mitigation technology than cellulosic transportation fuel. Second, I show, both conceptually and empirically, how environmental/energy policy interactions can increase the social cost of each policy. This has especially important implications for the future of the advanced renewable transportation fuel industry, which already faces significant production cost barriers. Finally, this is the first study to explore this policy-interaction hypothesis in a general equilibrium framework that accounts for linkages across both domestic and international markets.

This chapter is organized as follows. Section 5.2 reviews two strands of the existing literature. The first focuses on the relationship between market-based greenhouse gas policies and bioenergy production, while the second provides an overview on the economics of bioelectricity production. Section 5.3 provides a theoretical discussion useful for understanding the potential policy interactions between carbon-pricing policies and renewable transportation fuel standards. Section 5.4 discusses the modifications made to FARM in order to evaluate bioelectricity production, as well as defining policy scenarios and assumptions. Section 5.5 reports results, focusing on energy production portfolios in the electricity and transportation fuel sectors. This section also provides welfare estimates associated with the various policies.

## 5.2 Literature Review

Due to the public good characteristics of GHG mitigation, policy intervention is most likely required to avoid undesired effects associated with climate change. Economists have long suggested that optimal abatement levels can, theoretically, be achieved by imposing a cost on the production of externalities (Baumol and Oates, 1988; Pigou, 1932; Montgomery, 1972). Examples include Pigouvian effluent taxes or cap-and-trade schemes, and are more generally referred to here as market-based GHG mitigation policies. Other solutions include sector-specific intensity standards and technology-specific policies, such as renewable energy subsidies or production mandates. These policies have proven to be more feasible politically and are therefore more likely at a national or regional scale. However, recent literature has shown that quantity-based GHG mitigation policies are inferior to market-based approaches (Palmer and Burtraw, 2005; Morris, 2009; Bird et al., 2011; Palmer et al., 2011). These studies also evaluate the redundancy of interacting quantity and market-based mitigation policies, and show that quantity mandates tend to increase the overall cost of reducing emissions, even when implemented jointly with more efficient, market-based, policies. However, the literature to date has focused primarily on general energy sector interactions. Unique interactions may appear with regards to bioenergy as a result of the competition for biomass and land from various primary energy sectors.

### 5.2.1 GHG Policies and Bioenergy Production

Several studies have explored the effect of a GHG-pricing policy (such as a carbon tax or cap-and-trade) on biofuels. Using large-scale economic equilibrium models Schneider and McCarl (2003) and Timilsina et al. (2011) find that establishing a price on carbon does little to incentivize the production of conventional biofuels. This result appears to hold even for high $CO_2$ prices. The key economic factor driving the result for conventional biofuels is an income effect that reduces overall transportation fuel demand. While a carbon tax would provide incentives for fuel switching away from crude oil, an income effect also reduces overall demand for transportation fuels as crude oil becomes more expensive. The net effect, according to these studies, is that blended-gasoline demand falls enough to offset any relative price advantage conferred to biofuel. In other words, GHG mitigation in the transportation fuel sector comes from lower consumption, not technology switching. Neither of these studies considered the effect of market-based carbon policies on advanced biofuel technologies, such as fuels derived from cellulosic feedstocks.

For advanced fuels, the literature is limited. Hellwinckel et al. (2010) show that including dedicated energy crops in a GHG offset program will provide incentives to produce large quantities of perennial grasses. However, their analysis is limited to the agricultural sector and does capture essential factors such as current and future advanced biofuel refining costs, prices of other backstop technologies, and broader transportation fuel market dynamics. Other studies, such as Plevin and Mueller (2008) use detailed techno-economic models to predict the impact of domestic greenhouse gas pricing policies on the direct costs of liquid biofuel production. Production costs are likely to increase slightly, due to fossil fuel use in the refining process. However, techno-economic models do not usually consider economy-wide demand adjustments in energy markets, and often underestimate possible reductions in final transportation fuel demand.

Using the FASOM partial equilibrium model, Rose and Mccarl (2010) show that for carbon prices under \$10/tCO$_2$e, biomass could supply up to 14 exajoules of energy for electricity (prior to power plant efficiency losses). Almost 50% of this would come from perennial grasses, such as switchgrass, with the remainder obtained primarily from agricultural residues. However, this only occurs once the cellulosic mandate in the Renewable Fuel Standard expires, at which point a cap-and-trade policy causes biomass to be reallocated from the transportation fuel sector to the electricity sector. The implication is that a bioelectricity sector is not likely to develop given a binding renewable transportation fuel mandate due to competition-induced price increases in cellulosic biomass markets. However, this dynamic is only mentioned indirectly (rather than modeled explicitly) since it is not a central component of the study.

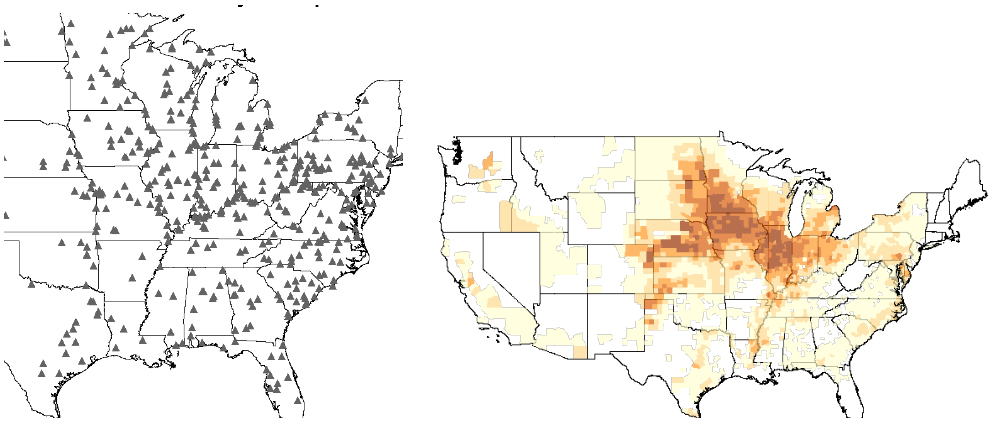
Thompson et al. (2010b) appears to be the only study in the literature that directly addresses the effects of interacting two explicit bioenergy policies with a GHG cap-and-trade policy. Using the FAPRI/CARD partial equilibrium model, discussed in Chapter 2, the authors simulate the impacts of a hypothetical GHG-pricing policy along with a bioelectricity mandate on the compliance costs of the Renewable Fuel Standard. Their findings suggest that so long as cellulosic subsidies are in place and biomass supply is relatively elastic, bioelectricity production does not increase the cost of meeting the Renewable Fuel Standard. This results suggests that introducing a bioelectricity standard or cap-and-trade policy is not likely to impair the development of the cellulosic biofuel industry (contingent on additional industry subsidies). However, the study does not address the reverse effect of the RFS on compliance costs of climate policy. A general equilibrium approach is more suited for this alternative perspective.

Research exploring the general equilibrium effects of GHG reduction policies on bioelectricity is limited. Ignaciuk et al. (2006) find that agricultural residues in Poland are able to provide 2-3% of the nation's electricity under 10% and 25% emissions reduction requirements. They suggest that dedicated energy crops are required in order to attain higher levels. Using agricultural residues they find a very modest impact on other agricultural sectors, although the use of dedicated energy crops for energy production is likely to amplify these impacts as biomass crops compete with food commodities for land resource.

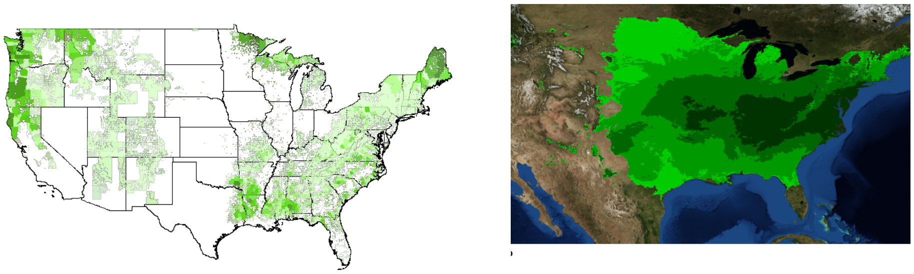
### 5.2.2 Economics of Bioelectricity Production

Bioelectricity refers to a variety of technology platforms that convert raw biomass into electricity (refer to McKendry, 2002, for a review of biomass to energy conversion processes). Several thermochemical processes are available including direct combustion and gasification. The latter technology typically involves specialized biomass electricity generation facilities where biomass is converted into syngas, which can then be converted to electricity in high efficiency gas turbines. Direct combustion electricity technologies often involve mixing biomass feedstocks with other fuels in existing combustion facilities (referred to as cofiring). This process has lower biomass energy conversion efficiencies but is appealing because of the large coal-fired electric power plant infrastructure throughout the world.

A cursory overview of the existing electric power infrastructure in the United States suggests that biomass cofiring is a very real possibility. Panel (a) in Figure 5.1 shows the location of coal-fired power plants that are currently operating. Panels (b)-(d) show recent projections of the regional supply of cellulosic biomass by feedstock type (National Renewable Energy Laboratory, 2012; U.S. Department of Energy, 2012). Several coal-fired electric power plants have conducted feasibility studies and pilot tests to examine the economics of integrating biomass into coal-fired boilers. Additionally, Haq (2001) reports ten commercial units throughout the United States that cofired biomass with coal, at levels ranging from 1-40% of total heat input (all but two facilities operated at levels under 10%). Feedstocks include woody biomass (primarily woodmill and forestry residues), municipal/commercial solid waste, agricultural residues, and occasionally dedicated biomass crops. A more recent study (De and Assadi, 2009) reports an additional eight facilities testing cofiring feasibility, most of which use wood waste.



(a) Coal-fired Power Plants (b) Corn Stover



(c) Forest Residues (d) Switchgrass

Figure 5.1: Bioelectricity Feedstock Availability

Federal renewable electricity mandates are not currently in place in the United States. However, there are a variety of state/regional renewable energy policies, the most common of which is a Renewable Portfolio Standard, implemented via renewable electricity credit trading markets (similar in many ways to the Renewable Fuel Standard). 29 states have RPS laws (21 of which are non-voluntary) that allow for the inclusion of biomass combustion technologies (DSIRE, 2012).

Several European Union member nations have also had considerable experience with these technologies. Ofgem (2012) reports that 30 coal-fired stations in the United Kingdom cofire biomass, 28 of which receive accreditation under the UK Renewables Obligation regulations that requires 15% of the nation's electricity to be produced from renewable energy resources by 2020. A broader EU mandate requires 20% of total electricity consumption to come from renewable energy, implemented primarily through national feed-in tariffs (Kangas et al., 2009). Not all EU countries allow biomass cofiring. Hansson et al. (2009) estimate that the EU has the potential to produce 50-90 terawatt hours (TWh) of electricity through cofiring with coal.[23] The International Energy Agency Bioenergy 32 Task Force reports that approximately 150 coal-fired units worldwide have cofired biomass (International Energy Agency, 2012).

When evaluating the economic feasibility of cofiring biomass for electricity, the operator of a coal-fired electric power plant must consider the relative costs of coal and biomass. Figure 5.2 shows the average price of coal in the U.S. over time on a \$/million btu basis. For comparison, biomass prices for several feedstocks (based on higher heating values) are also shown. Switchgrass and Miscanthus are shown at several plausible breakeven price levels (excluding the opportunity cost of land). Energy content values are taken from Collura et al. (2006) for miscanthus and Qin et al. (2006) for switchgrass. Willow and woodwaste are based on break-even prices and energy content values reported in Nienow et al. (1999). It is clear that the economic viability of cofiring will strongly depend on the type of coal being used, which varies by region and facility. The appeal, from a mitigation perspective, of biomass cofiring, is that aside from fuel-switching, relatively minor additional costs need to be incurred to make short-term emissions reductions. The additional non-feedstock costs include capital and maintenance costs that are necessary in order to retrofit an existing coal-fired electric power plant to utilize biomass in the boiler. A market-based GHG mitigation policy that increases the price of coal could certainly effect the economic viability of renewable biomass as a backstop energy resource in the electric power sector. Several studies have

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[23] For reference, in 2010, the entire EU produced approximately 3,330 TWh of electricity.

explored the feasibility of bioelectricity in the presence of a GHG mitigation policy. De and Assadi (2009) report techno-economic costs associated with retrofitting eleven U.S. coal-fired power plants for biomass cofiring, based on actual cofiring test trials. They find carbon abatement costs from fuel switching to be extremely low (around \$4/ton$CO_2$e) and fairly insensitive to cofiring levels (% biomass used), biomass price, or power plant capacity. Kangas et al. (2009) look at the effect of various renewable energy and GHG mitigation policies on cofiring operations in the European Union. They find that relatively small price incentives induce cofiring of woody biomass at levels from 2-7% (energy content equivalent).

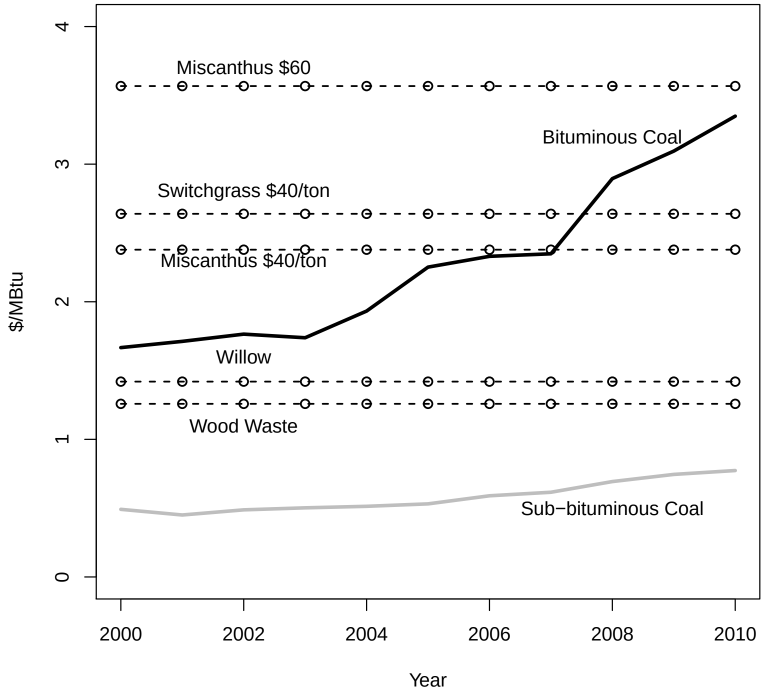

Figure 5.2: Unit Costs of Coal and Biomass from 2000-2010

These dynamics have not been well-studied for the United States where existing liquid biofuel policies are currently in place. Furthermore, coal is abundant and inexpensive in the U.S. but could be significantly impacted by the implementation of a greenhouse gas mitigation policy. Consistent with Schneider and McCarl (2003) and Rose and Mccarl (2010), the results presented below suggest that bioelectricity is an important mitigation option under a carbon pricing policy. Also consistent with implicit assumptions in Rose and Mccarl (2010), results of this study show directly that the concurrent presence of a renewable biofuel mandate alters the economic feasibility of bioelectricity as biomass prices are set at the margin by the transportation sector. This in turn raises the relative biomass-coal cost ratio and causes the economy to adopt mitigation alternatives elsewhere. The analysis takes an additional step by considering the efficiency implications of concurrently modeling a cap-and-trade policy with a binding cellulosic biofuel standard.

## 5.3 Theoretical Overview

Both market-based policies to reduce greenhouse gas emissions and quantity-mandates to promote renewable transportation fuels in the U.S. can be expected to have economy-wide consequences at both a domestic and global scale. This section provides a conceptual overview of some of the potential policy-induced effects of jointly implementing GHG-pricing policy and renewable transportation fuel mandates.

### 5.3.1 Domestic Policy Effects

This study is focused on competition between the electricity and transportation fuel sectors for biomass. This section will restrict attention to the market for biomass, and in particular, biomass that can be used to meet the cellulosic biofuel mandate in the Renewable Fuel Standard. A hypothetical market is shown in Figure 5.3. Biomass supply shows the total feedstock quantity that farmers are willing to supply at a given market price. Initial biomass

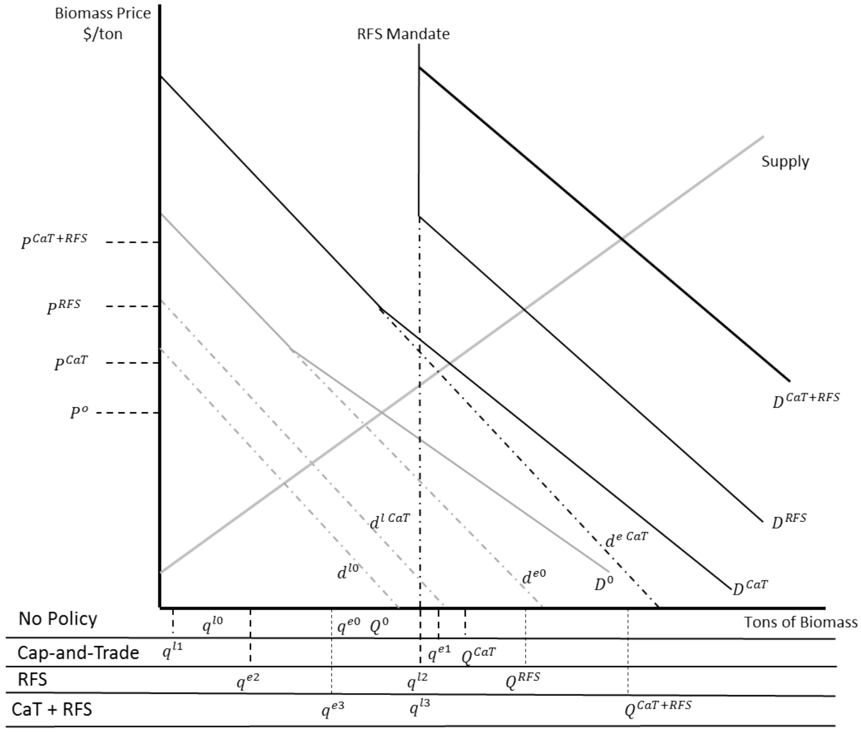

Figure 5.3: Biomass Market Effects of Bioenergy Policies

demand in the market $D^0$ is segmented into demand by the transportation fuel sector ($d^{l0}$) and the electricity sector ($d^{e1}$). Market supply and demand curves are shown as solid lines and demand curves for individual sectors are shown as hatched lines. For simplicity, assume that supply and demand schedules are linear. With no policy intervention, the market clears at price $P^0$ and quantity $Q^0$, with the majority of biomass consumed in the bioelectricity sector ($q^{e0}$). The remainder, $q^{l0}$, is used for cellulosic transportation fuel production.

The impact of both policy actions considered, cap-and-trade and the RFS, are also presented in Figure 5.3. First, consider the impacts of implementing a cap-and-trade policy. A market price for carbon increases biomass demand from both the cellulosic biofuel and bioelectricity sectors, as both are potential backstop technologies for petroleum and coal, respectively. Due to the factors discussed in Section 5.2, assume that a carbon price increases the electricity sector's demand for biomass ($d^{eCaT}$) by a proportionally greater level relative to transportation fuel ($d^{lCaT}$). At the new market clearing price, $P^{\mathrm{CaT}}$, the use of biomass for electricity production increases to $q^{e1}$ and use for cellulosic biofuel production declines to $q^{l1}$.

This result is reversed under a cellulosic mandate in Renewable Fuel Standard.[24] Assuming a constant biomass-to-fuel conversion ratio and binding RFS, demand for biomass from the transportation sector becomes fixed at $q^{l2}$. Market demand shifts to $D^{\mathrm{RFS}}$ and the equilibrium price increases to $P^{\mathrm{RFS}}$. At this price, biomass used for electricity production drops to $q^{e2}$. Under the hypothetical assumptions made here, there is still a residual demand from the electricity sector for biomass. The equilibrium price, $P^{\mathrm{RFS}}$, will be above what it would have been if price was set entirely by the cellulosic transportation fuel market (where the mandate intersects supply). Policy-induced competition for biomass will increase the unit cost of production for cellulosic biofuel by ($P^{\mathrm{RFS}} - P^0$), due to the higher price of biomass. This higher price must be fully absorbed by the transportation fuel sector and represents a net increase in the cost of achieving production targets set by the Renewable Fuel Standard.

Finally, consider the effects of both policies enacted simultaneously. Biomass price increases beyond the levels in either individual policy, to $P^{\mathrm{CaT+RFS}}$. This exacerbates the compliance cost of the meeting the RFS, as the higher price is fully capitalized into the variable costs of cellulosic biofuel refineries. In a well-functioning RFS compliance market, this effect is likely to be observed in higher Renewable Identification Number (RIN) prices, which must be submitted to the Environmental Protection Agency by regulated blending

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[24] Note that the RFS technically mandates renewable fuel, although for simplicity assume that this creates a biomass mandate as well.

facilities. There is also an analogous distorting effect in the GHG compliance markets (ie, markets for tradeable $CO_2$ permits). For any given level of bioelectricity production, the price of biomass is higher due to the presence of the RFS. However, unlike the demand for biomass from the transportation sector, demand for biomass from the electricity sector is not perfectly inelastic. The higher biomass prices will result in lower bioelectricity production, shifting GHG mitigation into other sectors of the economy. Assuming that the bioelectricity demand curve is not completely elastic, the overall effect, discussed below, will be to increase the economy-wide cost of greenhouse gas abatement.

The economic efficiency implications of enacting a cap-and-trade policy and renewable transportation fuel mandate simultaneously can be evaluated by considering any additional cost of compliance for each program due to competition for biomass induced by the other policy. For example, Figure 5.4 shows the effect of increasing greenhouse gas reduction requirements on the cost of meeting a fixed RFS production target. The solid black lines in the graph on the right show hypothetical biomass market demand curves with both policies in place. As the GHG target becomes more aggressive, electricity demand for biomass increases (the RFS target remains fixed). The cap-and-trade policy therefore increases the price of biomass for the same level of renewable transportation fuel production. As mentioned previously, the RFS must be met and higher biomass price will be fully absorbed in the RFS compliance market, thereby raising the social cost of meeting a given renewable fuel target. Assuming full pass-through of production costs, transportation fuel consumers will bear the burden of higher biomass prices. $C^{\mathrm{RFS}}(1)$-$C^{\mathrm{RFS}}(3)$ represent the marginal cost of RFS compliance as the GHG mitigation target increases. This RFS policy cost, as a function of the GHG reduction target, is shown in the left graph of Figure 5.4. It is convex to the origin

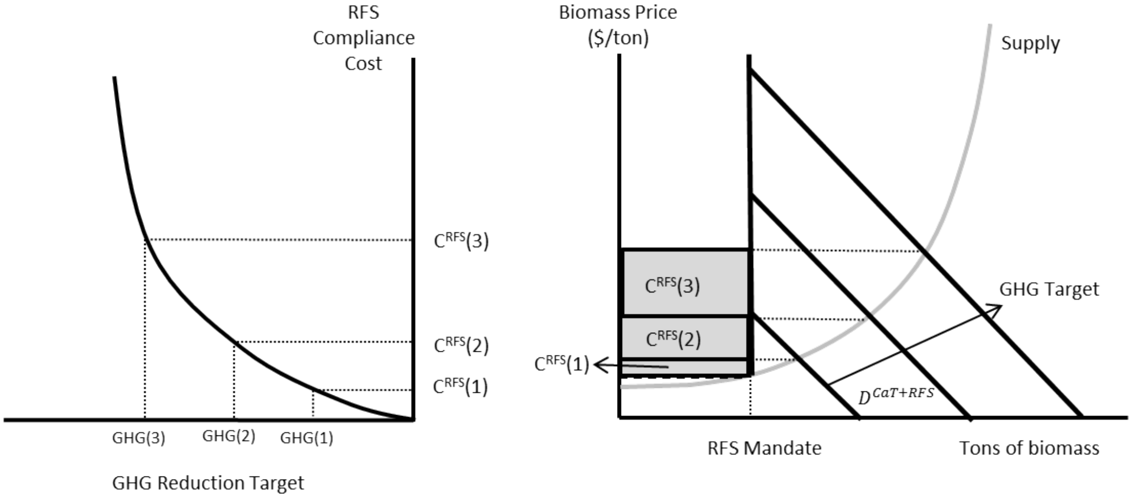

Figure 5.4: Cap-and-Trade Impact on RFS Compliance Cost

due to the assumption that biomass supply experiences diminishing marginal returns to key inputs, which is discussed in more detail below.

Similarly, we can assess the effect of the RFS on the cost of achieving a greenhouse gas reduction target (ie, the marginal carbon abatement cost). This is shown in Figure 5.5. Assuming that a cap-and-trade policy induces demand for biomass from the electricity sector at $D^{\mathrm{CaT}}$, shown in the right graph, increasing the RFS mandate from zero to RFS(2) has the effect of increasing the marginal carbon abatement cost (MAC) curve, shown in the left graph. Even if one assumes that life-cycle greenhouse gas emissions for renewable transportation fuel are zero, so long as the cost of producing cellulosic biofuel is higher than other potential mitigation options, the economy-wide MAC must increase. The cost to society of this interaction can be measured as the difference in the integral of the optimal carbon abatement path (MAC) and the abatement path when biomass is diverted away from electricity production into renewable transportation fuel production ($\mathrm{MAC}^{RFS1}$ and $\mathrm{MAC}^{RFS2}$), evaluated over the range of emissions reductions. By definition, any deviation

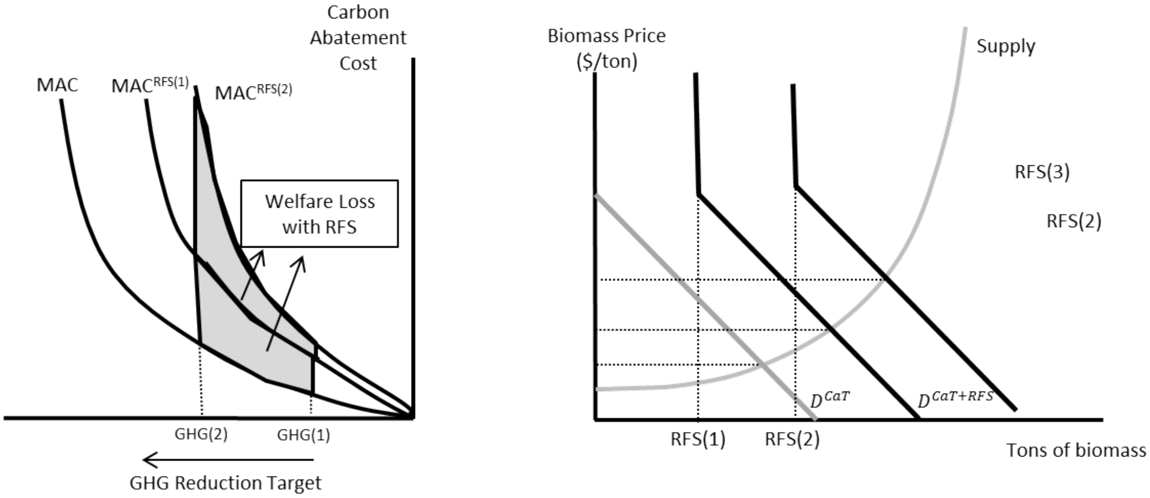

Figure 5.5: RFS Impact on Marginal Carbon Abatement Cost

from the optimal energy technology portfolio (implicit in the optimal abatement cost curve) must be less efficient than alternative abatement strategies.

The magnitude of these policy-induced effects will depend on several factors, including:

- Supply and demand elasticities in biomass markets
- The marginal costs of non-biomass renewable electricity and natural gas
- Efficiency improvements and scale effects in the cellulosic refining sector

Perhaps the most important factor is the elasticity of biomass supply. Inelastic biomass supply will increase the compliance cost of both RFS and cap-and-trade policies, while higher supply elasticities will reduce these costs. The biomass supply elasticity is primarily determined by two factors: the degree to which land can be shifted from other uses into biomass production and the yield responsiveness to management practices, such as nutrient application. Several recent studies have shown that yield response is relatively low for several candidate bioenergy feedstocks (Aravindhakshan et al., 2011; Shield et al., 2012).[25] Land for bioenergy production can come from displacing existing crop acreage or converting land that is not currently used for agricultural production. The cost of shifting existing agricultural land into bioenergy feedstock production is determined by the value of the agricultural commodities being displaced whereas the cost of growing biomass on "marginal" land is primarily a function of yield declines associated with less productive soils. High agricultural commodity prices for non-bioenergy crops and low yields reported on unproductive lands suggest that biomass supply is likely to be relatively inelastic, especially for non-residue feedstocks. These factors imply that biomass producers respond less to price changes as production increases.[26] Therefore, as greenhouse gas reduction targets and RFS cellulosic biofuel mandates become more aggressive, we would expect program compliance costs to increase (and likely at an increasing rate).

The electricity sector's elasticity of demand for biomass will also influence the economy-wide cost of GHG abatement. If other mitigation options exist, at comparable costs per unit of emissions reduction, biomass demand would be relatively elastic, and therefore higher biomass prices, due to the RFS, will not have a large impact on overall abatement costs. For example, if natural gas and non-biomass renewable electricity, such as wind, solar, geothermal, etc., can easily displace coal-fired generation, the higher cost of biomass will not necessarily create large inefficiencies in compliance markets. One might suggest, however, that this may not be the case, especially in the short-run, as intermittency concerns with

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[25] Low perennial grass yield responses have not been shown conclusively and exhibit considerable regional heterogeneity (Nikièma et al., 2011).

[26] Recall from in the FARM structural equations that unit cost functions are derived from CES, production functions, implying that all else equal, supply becomes less price responsive as production increases.

renewable electricity sources and high capital costs associated with building new generation facilities make the transition away from coal more costly. This accounts for the growing appeal to cofire biomass in existing coal-fired power plants, since the industry can capitalize on already sunk infrastructure costs.

This section has highlighted interactions in domestic biomass markets, which represent only a small fraction of the domestic energy complex, and will continue to do so even as bioenergy markets continue to develop. However, bioenergy markets are integrated into a larger energy and agricultural system, which suggests that response to policy is likely to extend beyond the bioenergy sector. For this reason, an economy-wide modeling approach is most appropriate for evaluating the RFS and GHG mitigation policies.

### 5.3.2 International Trade Effects

In addition to the domestic effects of bioenergy policy, the fact that the United States is a major economic actor in global agricultural and energy commodity markets suggests that domestic bioenergy policies may also have global effects, which can soften or enhance domestic impacts. The magnitude of these effects are largely determined by the degree to which U.S. policy alters the *terms of trade* for individual countries or regions. Terms of trade is defined as a nation's export price index relative to its import price index and is used to deflate real income in an open-economy.

The U.S. is both a large net exporter of agricultural commodities as well as a large net energy importer. In energy markets, domestic policies that reduce U.S. demand for fossil fuels are likely to affect global energy prices. Paltsev et al. (2007) show that a U.S. hypothetical cap-and-trade policy improves the terms of trade for fossil fuel-importing regions and reduces rents in fossil fuel-exporting regions. Ceteris paribus, this is projected to result in subsequent welfare increases (decreases) for fossil fuel-importing (exporting) regions. Domestic biofuel policy induces in a similar terms of trade effect in international energy markets, as U.S. demand for imported fossil fuels decline, causing global fossil fuel prices to decline as well.[27]

The effect of U.S. biofuel policy on global agricultural commodity markets is slightly more complex. Conventional ethanol production in the United States relies almost exclusively on corn grain, and therefore increased domestic demand for corn from the ethanol sector is predicted to lower U.S. corn grain exports. A large negative export shock from the U.S. therefore increases global corn grain prices, predictably altering the terms of trade for net grain importing and exporting regions. Cellulosic biomass, however, is not a globally traded commodity, yet could still compete with traded agricultural commodities for cropland (either directly or indirectly). Which commodities will be affected and the magnitude of any export shock resulting indirectly from diverting land into biomass production will depend on the complex interaction of agricultural input and commodity market elasticities. While the FARM model predicts how U.S. cellulosic biofuel production impacts global markets, important cross-price elasticities between biomass and conventional agricultural markets cannot be adequately validated since such biomass markets are only beginning to develop. The magnitude of any international trade and welfare results should therefore be interpreted with caution. The purpose in this study is to highlight potential directional effects only.

## 5.4 Methodology and Policy Scenarios

The FARM model and GTAP 7 database are expanded in this study in order to understanding the effects of various bioenergy and GHG-reduction policies on bioenergy

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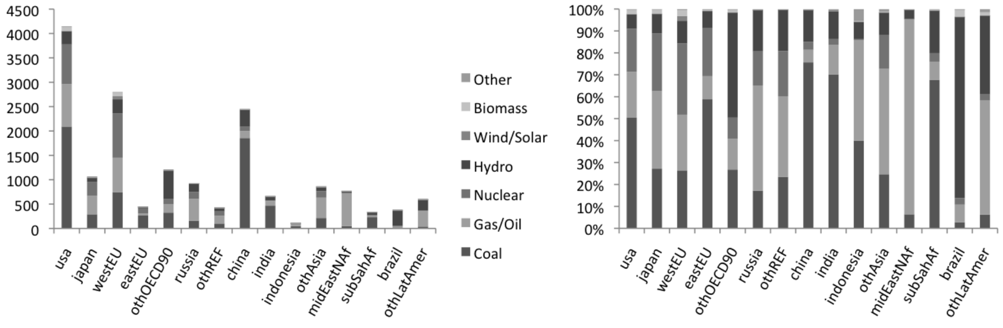
[27] As discussed in previous chapters, there are also "rebound effects" associated changes in global energy prices. Terms of trade improvements in energy importing regions may result in higher fossil fuel imports, offsetting some of the initial reduction in U.S. fossil fuel demand.

production in the U.S., as well as the impacts on global agricultural and energy commodity markets. The methodology follows the approach described in previous sections. Section 5.4.1 describes additional modifications that were necessary in order to incorporate a more detailed electricity production module, connections between bioelectricity and liquid biofuel, and energy accounting necessary to simulate greenhouse gas reduction policies. Section 5.4.2 outlines the various policy scenarios and any relevant assumptions.

### 5.4.1 Modifications to FARM

The liquid transportation fuel sector is structured very similarly to that described in Chapter 4. Several slight modifications have been made. First, the biomass feedstock used in the production process is assumed to be somewhat more generic than the switchgrass and corn stover sectors developed in Chapter 4. This allows the analysis to focus more on general land competition interactions between the electricity and transportation fuel sectors of the economy, rather than on the specific feedstock characteristics. Conventional ethanol is included in the analysis as an important source of demand for agricultural land. It is also important to include corn ethanol in the analysis as it could potentially be a GHG backstop technology for refined petroleum. As noted in Chapter 3, the FARM model includes energy accounting for fossil fuels. In order to properly integrate biofuels into a framework that allows for GHG policy analysis, I have assumed that the energy content of conventional ethanol sectors is two-thirds that of refined petroleum. The advanced biofuel sector is assumed to be a perfect substitute with refined petroleum on an energy content basis (Schnepf, 2010).

The original electricity sector in the benchmark data, “ely”, is expanded using production data from the International Energy Agency (IEA) in order to account for various types of electricity produced in each region. The “ely” production is decomposed into six new



(a) Total Production by Fuel Source (b) Generation Share by Fuel Source

Figure 5.6: 2004 Benchmark Electricity Production

sectors, based on the primary energy input used in the generation process. These six sectors include electricity from (1) coal, (2) natural gas and oil, (3) nuclear, (4) hydropower, (5) wind and solar, and (6) biomass.[28] 2004 production levels and shares are shown in Figure 5.6. The six sectors are aggregated into a single sector using a CES production function, "ely", and consumed by households and firms. The original GTAP database does not include certain primary factor endowments of nuclear material and renewable electricity resources hydro, wind, and solar. When introducing these sectors, a "fixed" factor endowment is supplied to each of these sectors, representing the economic value of these inputs. This approach is also taken in the EPPA model and is reflective of the fact that these resources have value in the production process but are not utilized by other sectors (Paltsev et al., 2005).

$CO_2$ emissions associated with the combustion of bioenergy feedstocks are assumed to be zero. This is justified on the grounds that such emissions are offset during the biomass growth phase. Indirect emissions associated with bioenergy due to the use of fossil fuels in the energy conversion process are still accounted for, implying that net emissions are likely to be slightly positive but still considerably lower than refined petroleum or coal-fired

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[28] "other" electricity production represents such a small fraction of production that it is dropped from the data set.

electricity. Emissions factors for fossil fuels are documented in Chapter 3. 2004 (base year) $CO_2$ emissions are estimated to be 5749.3 million metric tons (mmt). This is slightly lower (less than 5% )than the 6031.3 mmt estimated by the U.S. Department of Energy (Energy Information Administration, 2012c). This may modestly effect future emissions projections. Additionally, because the GHG policy is referenced to base year emissions assumptions, any error in base year measurement should affect all scenarios identically.

The biomass/land linkage between electricity and transportation fuel markets is shown in Figure 5.7. With limited land resources (ie, upward-sloping land supply), this linkage is crucial for analyzing various energy and environmental policies that divert land to biomass for energy production. The assumption is that a cellulosic feedstock can be used either for liquid biofuel production (fulfilling the cellulosic mandate in the RFS) or used as an input into a coal-fired electric power plant. The biomass is for energy-use only, although it will compete for with other agricultural sectors for land. This assumption also ignores the fact that some biomass feedstocks may be more suited to use in one energy industry over another. Feedstock heterogeneity and suitability for various end uses is more appropriately addressed using regional economic models that can explicitly account for greater market detail. The cost of the general equilibrium approach used here is the inability to directly address regional heterogeneity within the United States, which is likely to be important, especially in biomass feedstock markets. The advantage over models with more detailed representation of bioenergy markets is the ability to account for economy-wide adjustments outside the bioenergy sector. It should also be noted though that forestry byproducts and pulp/paper mill waste have long been used for combined heat and power (CHP) operations

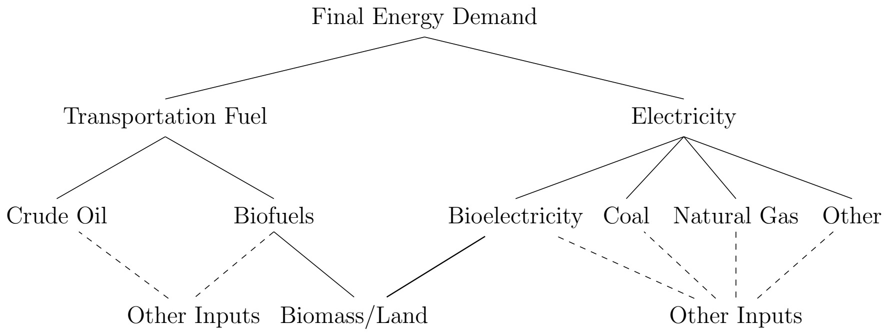

Figure 5.7: FARM Bioenergy Linkages

within the pulp/paper industry. The new bioelectricity is assumed to be separate from CHP activities.

Cost shares for the six new electricity sectors are shown in Table 5.1. Bioelectricity shares are assumed to be similar to the coal-fired electric power sector, with minor adjustments made to reflect differences in costs for fuel inputs. Additional costs resulting from retrofits and maintenance are included but only in a stylized fashion. Evidence suggests that these costs will vary in reality based on the characteristics of individual coal-fired units. Because I am simulating large-scale policy scenarios, with an emphasis on biomass market interactions, these simplifications are not expected to significantly alter the results.

### 5.4.2 Policy Scenarios and Assumptions

Several policy scenarios are considered. All scenarios cover a 40-year time horizon in four, ten-year timesteps. Population growth, energy effiency, and factor productivity changes from time period to time period follow the assumptions described in Chapter 3. The first scenario, **Business as Usual** (BAU), consists of no greenhouse gas reduction policy and no bioenergy mandates. The second scenario, **Cap-and-Trade** (CaT), imposes $CO_2$ reduction mandates in each time period. The reductions would reduce U.S. emissions by 50% below

Table 5.1: FARM Electricity Sector Cost Shares: Technologies are separated by primary resource input

| | Coal | Natural Gas | Nuclear | Hydro | Solar/Wind | Biomass |
|---|---|---|---|---|---|---|
| Primary Factors | | | | | | |
| Labor | 0.12 | 0.08 | 0.16 | 0.16 | 0.16 | 0.18 |
| Capital | 0.35 | 0.23 | 0.23 | 0.23 | 0.42 | 0.26 |
| Fixed Factor | - | - | 0.23 | 0.23 | 0.05 | - |
| Intermediate Inputs | | | | | | |
| Coal | 0.23 | - | - | - | - | - |
| Natural Gas | - | 0.51 | - | - | - | - |
| Biomass | - | - | - | - | - | 0.13 |
| Electricity | 0.05 | 0.03 | 0.07 | 0.07 | 0.07 | 0.08 |
| Transport | 0.04 | 0.02 | 0.05 | 0.05 | 0.05 | 0.05 |
| Services | 0.09 | 0.06 | 0.12 | 0.12 | 0.12 | 0.14 |
| Other | 0.12 | 0.07 | 0.14 | 0.14 | 0.14 | 0.16 |
| Total | 100% | 100% | 100% | 100% | 100% | 100% |

2004 levels, by 2050, and are distributed linearly across the time periods (a 10% reduction mandate every ten years). The policy is implemented through a downstream marketable permits system where industries using fossil fuels face an endogenously determined carbon price, reflecting the value of an emissions permit. The third and fourth scenarios are two liquid biofuel mandates. The third scenario (**RFS-Conv**) implements the 10 billion gallon (gasoline equivalents) conventional ethanol mandate in 2014 and assumes levels remain for the duration of the simulation. The fourth scenario (**RFS-Full**) implements a 1.5 billion gallon (gasoline equivalents) cellulosic biofuel mandate beginning in 2014 *in addition to* the conventional ethanol mandate. The cellulosic biofuel is assumed to use a dedicated energy crop feedstock that requires productive land (identical to the switchgrass sector in previous chapters). The required mandate for cellulosic biofuel is lower than in Chapter 4. This is done in order to gain insight into the *marginal* effects of the RFS mandate for advanced biofuel. This also eases the computational burden of solving large-scale emissions reduction scenarios in conjunction with the RFS requirements. The fifth scenario (**CaT+RFS**) implements the cap-and-trade policy in addition to the RFS-Full policy.

Nuclear power and hydroelectricity are assumed to remain constant at 2004 levels throughout the simulations. This assumption is made for several reasons. First, the public concern regarding the safety and environmental effects of these technologies has made their future highly uncertain. While new nuclear facilities may come into production in the United States, the concern over the technology is likely to prevent new generation levels from exceeding the decline in generation due to the retirement of old facilities. The availability of additional hydroelectric resources in the United States also remains unclear. Attitudes towards nuclear and hydroelectric power could certainly change in the future, in which case both technologies would be important $CO_2$ abatement options in the electricity sector.

The cap-and-trade mitigation scenarios are simulated by placing a constraint on $CO_2$ emissions for the United States in each time period, beginning in 2004. The emissions constraint then allows for a $CO_2$ price to be solved endogenously within the model. This price can be interpreted either as the optimal carbon tax or the price of an emissions permit under a cap-and-trade scenario. The government generates revenues through this policy, and if interpreted as a cap-and-trade program, these revenues would represent the value of auctioned emissions permits. All revenue generated by the government through this policy is recycled back to households, thus making the policy revenue neutral.

### 5.5 Results

Results are presented here according to two themes. First, in section 5.5.1, results are given for energy production portfolios and consequent $CO_2$ emissions. The focus then turns in section 5.5.2 to the welfare implications of the various policy simulations.

### 5.5.1 Energy Production

Table 5.2 shows the breakdown of total projected transportation fuel use across refined petroleum, conventional, and cellulosic biofuels. Note that under the BAU and Cap-and-Trade scenarios, conventional ethanol makes a very minimal contribution to the transportation fuel sector. Ethanol from corn increases to nearly 8.1% of the transportation fuel blend, but as a result of the decline in overall transportation fuel use, rather than a large increase in biofuel production. Ethanol production never exceeds 0.311 EJ (3.5 billion gallons ethanol equivalent), which constitutes a fairly trivial increase above 2004 production levels. Cellulosic biofuel levels remain essentially flat and do not contribute substantially to the U.S. transportation fuel blend. This finding is consistent with Timilsina et al. (2011) for conventional ethanol that cap-and-trade proposals do little to stimulate ethanol production. This is the first study to suggest that a similar result is found for advanced biofuels. This result should be approached with caution, as future developments, cost-reductions, technological breakthroughs, and other important factors are not included in these projections. Policies that provide direct incentives to biofuel production perform as expected and appear to have little interaction (in terms of production levels) with a cap-and-trade policy. Biofuel shares are high, but overall refined petroleum displacement between a cap-and-trade only and cap-and-trade + RFS policy is minimal. The interaction between biofuel policies and refined petroleum levels in the United States was discussed in detail in Chapter 4.

Optimal technology mixes in both the electricity and transportation fuel sectors vary considerably across the three scenarios. The RFS scenario for conventional ethanol mandates is excluded because electricity generation results are virtually identical to the BAU scenario.

Table 5.2: U.S. Transportation Fuel Mix: All quantities are in exajoules (EJ). Percentages of the gasoline fuel mix are in parentheses. 1 billion gallons ethanol = 0.089 EJ. 1 billion gallons refined petroleum = 0.132 EJ.

| | **Business as Usual** | | | | **RFS-Full** | | | |
|---|---|---|---|---|---|---|---|---|
| | **2014** | **2022** | **2032** | **2042** | **2014** | **2022** | **2032** | **2042** |
| Refined Petroleum | 7.39 | 6.37 | 5.62 | 5.08 | 7.27 | 6.28 | 5.56 | 5.04 |
| | (.961) | (.955) | (.948) | (.941) | (.854) | (.834) | (.816) | (.800) |
| Conventional Biofuel | 0.294 | 0.293 | 0.299 | 0.311 | 1.174 | 1.174 | 1.174 | 1.174 |
| | (.038) | (.044) | (.050) | (.058) | (.138) | (.156) | (.172) | (.186) |
| Cellulosic Biofuel | 0.008 | 0.008 | 0.009 | 0.009 | 0.073 | 0.078 | 0.080 | 0.083 |
| | (.001) | (.001) | (.001) | (.002) | (.009) | (.010) | (.012) | (.013) |
| **Total** | **7.70** | **6.67** | **5.93** | **5.40** | **8.52** | **7.53** | **6.81** | **6.30** |

| | **Cap-and-Trade** | | | | **CaT+RFS** | | | |
|---|---|---|---|---|---|---|---|---|
| | **2014** | **2022** | **2032** | **2042** | **2014** | **2022** | **2032** | **2042** |
| Refined Petroleum | 7.02 | 5.59 | 4.45 | 3.53 | 6.89 | 5.50 | 4.38 | 3.48 |
| | (.958) | (.948) | (.935) | (.917) | (.847) | (.814) | (.777) | (.735) |
| Conventional Biofuel | 0.297 | 0.298 | 0.303 | 0.311 | 1.174 | 1.174 | 1.174 | 1.174 |
| | (.041) | (.051) | (.064) | (.081) | (.144) | (.174) | (.208) | (.248) |
| Cellulosic Biofuel | 0.008 | 0.007 | 0.007 | 0.007 | 0.073 | 0.082 | 0.084 | 0.084 |
| | (.001) | (.001) | (.001) | (.002) | (.009) | (.012) | (.015) | (.018) |
| **Total** | **7.32** | **5.90** | **4.76** | **3.85** | **8.14** | **6.75** | **5.63** | **4.74** |

Figure 5.8 shows total electricity generation (in terawatt hours) broken down by primary fuel source. Several important observations can be made. First, when comparing the RFS-Full and BAU scenarios, bioelectricity production is almost entirely crowded out from the use of dedicated energy feedstocks for liquid biofuel production. This is a result of the higher cellulosic biomass price, created by the policy-induced increase in demand for cellulosic biofuel. In the abatement scenario (CaT), bioelectricity is an important mitigation technology, as production levels increase from 71 TWh in 2004 to 514 TWh in 2044 (a 622% increase). The CAT+RFS policy reduces bioelectricity production to 440 TWh in 2044. This decline appears moderate, although recall that this is result from only 1.5 billion gallons cellulosic biofuel production (14% of the 2022 mandated levels in RFS). Natural gas and non-hydro renewables (wind/solar) are also significant abatement technologies and contribute

greatly to the electricity portfolio as coal-fired electricity generation declines precipitously in the CaT abatement scenario. Natural gas electricity is an especially important abatement technology in earlier phases of the CaT policy, with non-hydro renewables playing a larger role in future abatement.

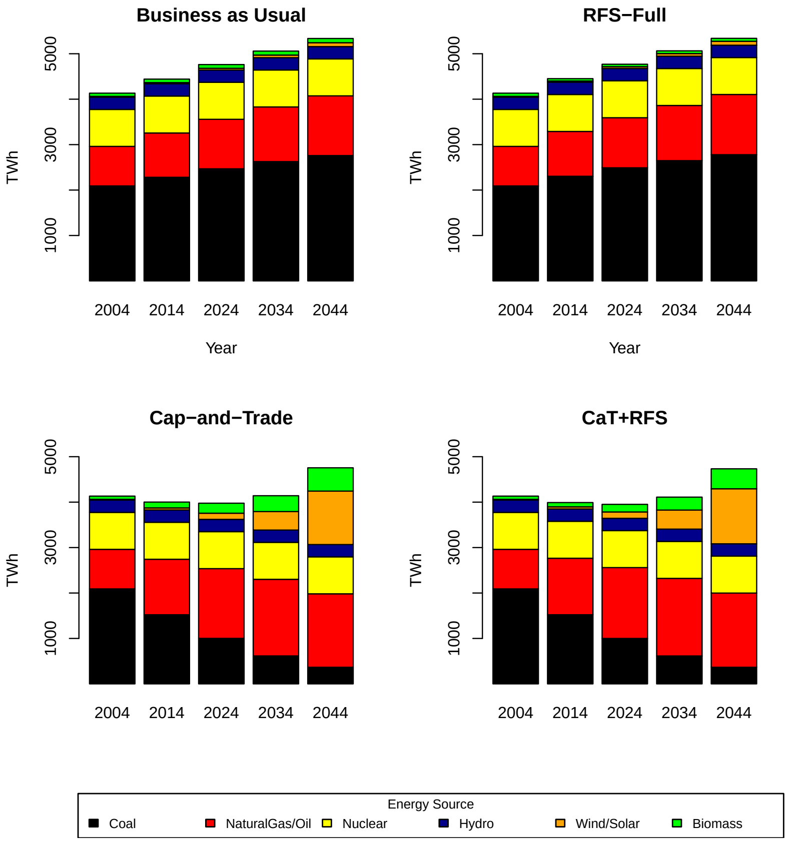

Figure 5.8: U.S. Electricity Generation Portfolio by Scenario: Production quantities are in terawatt hours

A more detailed graphical representation of electricity generation by fuel input is shown in Figure 5.9. Here we can more easily see the effects of interacting a cellulosic liquid biofuel mandate with the cap-and-trade policy. While the effects on coal-fired generation are negligible, the presence of the RFS has the effect of shifting generation away from bioelectricity and into natural gas and non-hydro renewable. Implementing the full 2022

RFS mandate (a 711% increase in cellulosic biofuel above the levels simulated here) can be expected to significantly exacerbate these results.

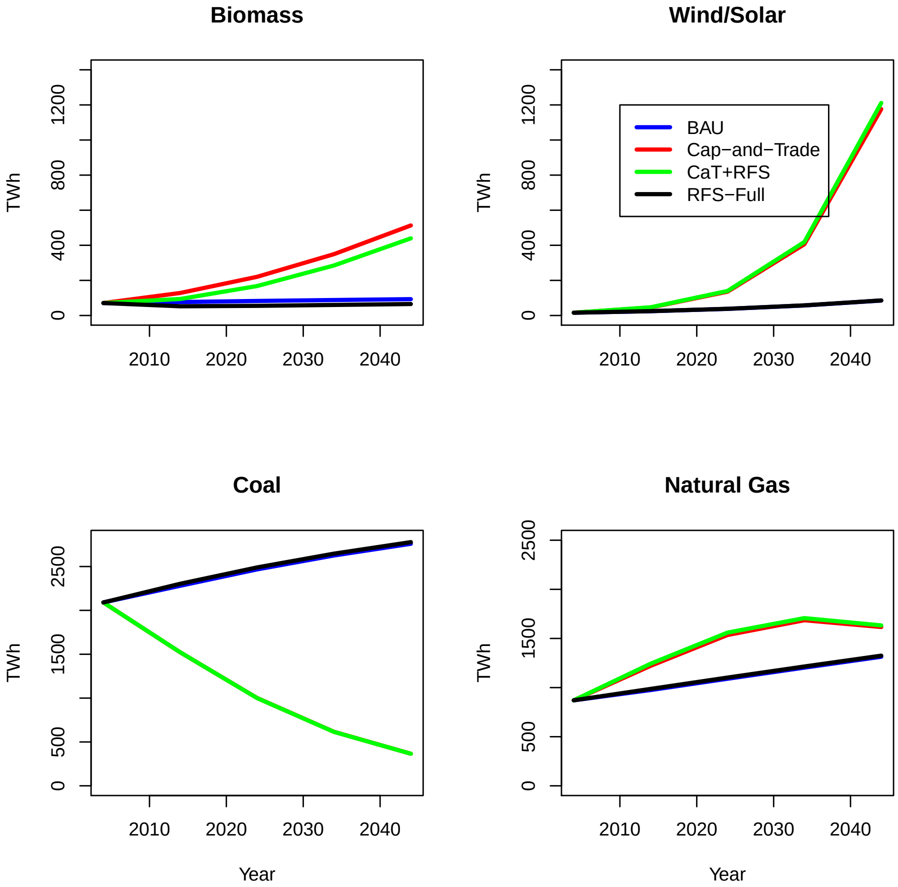

Figure 5.9: Policy Scenario Effects on Electricity Technologies: Production quantities are in Terawatt Hours

The effect of these various policies on $CO_2$ emissions is shown in Table 5.3. It is interesting to note that the RFS policies, in the absence of any direct $CO_2$ abatement policy, have nearly no effect on domestic emissions. While refined petroleum levels decline slightly in policies that have an RFS (due to higher blended fuel prices), the transportation sector is able to substitute (at very low levels) into natural gas, creating a minor rebound effect that offsets some of the emissions savings that would be expected from lower refined

Table 5.3: Projected $CO_2$ Emissions in the U.S. (million metric tons)

| | 2004 | 2014 | 2022 | 2032 | 2042 |
|---|---|---|---|---|---|
| BAU | 5749.3 | 6012.4 | 6286.7 | 6511.8 | 6688.5 |
| CaT | 5749.3 | 5174.1 | 4599.2 | 4024.3 | 3449.4 |
| RFS-Conv. | 5749.3 | 6024 | 6298.2 | 6523.1 | 6699.6 |
| RFS-Full | 5749.3 | 6034 | 6309.7 | 6534.6 | 6711 |

petroleum consumption. These effects are minor for the RFS-Full scenario. However, there is a similar market mechanism in the electricity sector. As the RFS targets divert biomass in transportation fuel production, bioelectricity production levels decline. With no incentives to reduce $CO_2$ emissions, the increase in the relative price of biomass causes larger quantities of coal to be used for electricity production. This has the effect of slightly increasing overall $CO_2$ emissions above the business as usual scenario. Emissions levels for the CaT and CaT+RFS are identical by definition, and therefore this rebound effect will not be observable. Instead market effects in the presence of a CaT are observed in alternative abatement technologies, such as non-hydro renewables and natural gas, as described above.

### 5.5.2 Welfare Effects

The economy-wide welfare impacts of the various policies for each region are measured as equivalent variation (EV), money-metric measure of household utility. Equivalent variation can be calculated in FARM based on differences in real income/expenditures by the representative regional household across the various scenarios, adjusted for any terms of trade price level effects. There are other methods of measuring welfare. For example one could measure consumer and producer surplus in specific markets, or changes in factor payments (such as real wages). Hertel (2002) argues for using aggregate household utility to evaluate agricultural and resource policies. In a general equilibrium context, EV provides a good measure of the economy-wide welfare effect of a given policy, including price /quantity adjustments in *all* markets, income effects, and tax/subsidy transfer payments. The policies analyzed in this study affect numerous sectors of the economy, suggesting that the use of a broad welfare measure is most appropriate.

All measures of equivalent variation are relative to the business-as-usual scenario. Mathematically, equivalent variation in region $r$ is:

$$EV_r = RA_r^1 * \prod_c \left(\frac{Pd_{c,r}^1}{Pd_{c,r}^0}\right)^{\alpha_c^d} \prod_c \left(\frac{Pi_{c,r}^1}{Pi_{c,r}^0}\right)^{\alpha_c^i} - RA_r^0$$

Recall from Chapter 3, that $RA_r$ is the disposable income of region $r$'s representative agent. $Pd_{c,r}$ and $Pi_{c,r}$ are the prices of domestic and imported commodity $c$ in region $r$, respectively. $\alpha_d$ and $\alpha_i$ are the household income value shares for each commodity, $c$, after minimum consumption requirements are met. Aggregating commodity prices using these value shares creates a Laspeyres terms of trade index (Reinsdorf, 2010). Superscript 0 indicates the business-as-usual scenario, and superscript 1 indicates the policy scenario being evaluated.

Table 5.4 shows welfare effects for the United States as a result of the four policies under consideration. Results are shown in both monetary terms, and as a percentage of projected GDP. As expected, stringent greenhouse gas emissions constraints result in a decline in welfare. This measure ignores any external social benefits associated with climate stabilization. The cap-and-trade welfare estimates are consistent with other estimates in the literature (Paltsev et al., 2007). We also observe that both renewable transportation fuel mandate scenarios (RFS-Conv adn RFS-Full) increase domestic welfare. This is attributable to two factors. First, imported oil, used for transportation fuel, is partially displaced by

Table 5.4: Policy-Induced Welfare Effects in the United States

| | **EV (% of GDP)** | | | | **EV (billion $US)** | | | |
|---|---|---|---|---|---|---|---|---|
| | 2014 | 2022 | 2032 | 2042 | 2014 | 2022 | 2032 | 2042 |
| Cap-and-Trade | -.08% | -.21% | -.39% | -.60% | -12.4 | -40.4 | -89.6 | -165.9 |
| CaT+RFS | -.05% | -.19% | -.37% | -.58% | -8.2 | -36.1 | -85 | -161.1 |
| RFS-Conv | .03% | .02% | .02% | .02% | 4.3 | 4.4 | 4.5 | 4.6 |
| RFS-Fuel | .03% | .02% | .02% | .02% | 4.2 | 4.3 | 4.5 | 4.6 |

biofuels produced domestically. In addition to increasing domestic agricultural production for transportation fuel production, a decline in imports improves the terms of trade for the United States in global oil markets. Acting with a degree of monopsony power, lower demand in the U.S. lowers the global oil price and therefore the rents that oil-exporting regions gain from oil production. The second factor responsible for the increase in domestic welfare is the terms of trade improvement in global agricultural commodity markets. The RFS mandates increase the price of traded commodities globally and thus benefit large agricultural commodity exporters, such as the U.S. The higher cost of producing and consuming biofuels (relative to refined petroleum), appears to be more than offset by these two factors. The joint policy scenario (CaT+RFS) results a minor improvement in domestic welfare compared to the CaT-only policy. This is due to the availability of low cost non-biomass mitigation substitutes in the domestic electricity sector and the improvement in U.S. terms of trade.

However, as shown in Figure 5.10, the overall cost of the joint policy is, as hypothesized in section 5.3, higher under the concurrent implementation of RFS mandates and a cap-and-trade mitigation policy. Because the simulated cellulosic biofuel level was only 1.5 billion gge, the blue line shows a projection of the MAC curve if the RFS is fully implemented at 10 billion gge. This was done by scaling the difference in the modeled MAC curves by a factor

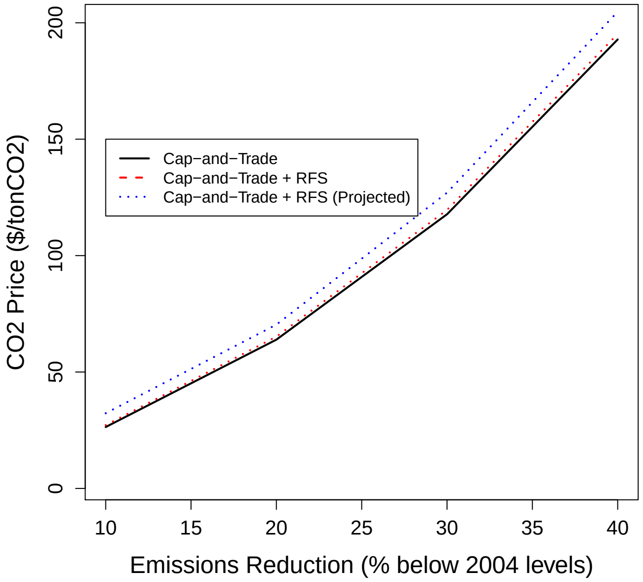

Figure 5.10: U.S. Marginal Abatement Cost Curves: Results from FARM Simulations

of 7. It should be noted that this projection is meant only to highlight the potential scale of welfare effects. Fully modelling a larger cellulosic biofuel mandate in conjunction with a CaT may create general equilibrium effects that shift the position of the projected MAC curve. A simply scaling factor is meant to provide a conservative estimate.

The higher abatement costs under CaT+RFS coupled with the fact that domestic welfare reductions are lower under CaT+RFS than CaT highlights that the dual policy is likely to have global distributional effects, as it is otherwise impossible to observe higher domestic abatement costs and greater welfare. These distributional issues are explored by reporting global welfare changes, decomposed by region, as shown in Figure 5.5. All welfare estimates are reported as changes from the business-as-usual scenario and as a percentage of simulated GDP. Comparing just across the RFS-Full and cap-and-trade policies, we see considerable heterogeneity in how different regions are impacted. These patterns are further complicated when comparing to the joint policy. In order to understand *why* welfare may be different regionally, across the policy scenarios, a simple regression was performed to decompose the variation in EV/GDP based on a region's position in global agricultural and energy commodity markets. Each region is categorized by its import and export share of global trade for oil and aggregated levels three highly traded agricultural commodities (coarse grains, wheat, and oil seeds). Results, shown in Table 5.6, generally, but not fully, confirm expectations. The terms of trade effect for oil markets is apparent across all three scenarios, but only for importing regions. Surprisingly, export share of the global oil trade does not appear to affect the impact of U.S. cap-and-trade or RFS policies. The terms of trade effect is very apparent in global agricultural commodity markets. As expected, the U.S. RFS tends to be negatively correlated with a region's import share, and positively correlated with export shares. The cap-and-trade policy has a generally adverse affect on welfare in regions with high import and export shares. The effect of implementing the RFS in addition to cap-and-trade is to then exacerbate adverse welfare impacts for agricultural commodity importing regions, and mute negative welfare impacts on exporting regions.

Because simulations only capture the marginal effect of cellulosic biofuel production, visualizing the global welfare effects of CaT vs. CaT-RFS is difficult. Applying the same linear scaling factor as was done with domestic marginal carbon abatement costs, reveals that if the advanced biofuel mandate of the RFS is fully implemented at 10 billion gge, the *additional* global welfare costs incurred when the RFS and CaT are jointly implemented can be considerable. Figure 5.11 shows the difference in the EV/GDP ratio in 2034 between the CaT policy and CaT-RFS policy. For example, a 10 billion gge standard (for both conventional and advanced biofuels) is expected to increase GDP-adjusted welfare measures

Table 5.5: Global Policy-Induced Welfare Effects: Equivalent Variation (relative to business-as-usual) as a fraction on GDP

| | Cap-and-Trade | | | | RFS-Full | | | | CaT+RFS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Japan | **2014** | **2024** | **2034** | **2044** | **2014** | **2024** | **2034** | **2044** | **2014** | **2024** | **2034** | **2044** |
| WestEU | .01 | .01 | .01 | 0.00 | -.003 | -.003 | -.003 | -.003 | .005 | .008 | .007 | .001 |
| EastEU | .00 | .00 | -.01 | -0.01 | .000 | .000 | .000 | .000 | .002 | -.001 | -.007 | -.014 |
| OthOECD90 | -.01 | -.03 | -.04 | -.05 | -.002 | -.002 | -.001 | -.001 | -.013 | -.027 | -.041 | -.051 |
| Russia | -.04 | -.07 | -.11 | -.15 | .000 | .001 | .001 | .002 | -.035 | -.074 | -.113 | -.149 |
| OthREF | -.01 | -.02 | -.02 | -.02 | .002 | .002 | .003 | .003 | -.011 | -.016 | -.018 | -.015 |
| China | -.03 | -.05 | -.07 | -.08 | -.002 | -.001 | -.001 | .000 | -.029 | -.051 | -.067 | -.081 |
| India | .00 | .00 | -.01 | -.02 | -.002 | -.002 | -.002 | -.002 | .002 | -.002 | -.012 | -.025 |
| Indonesia | .01 | .01 | .00 | .00 | -.001 | -.001 | .000 | .000 | .006 | .006 | .004 | .001 |
| OthAsia | .00 | .00 | -.01 | -.03 | -.001 | .000 | .000 | .000 | .002 | -.003 | -.013 | -.026 |
| MidEastNAf | .01 | .00 | -.02 | -.04 | -.002 | -.002 | -.002 | -.002 | .005 | -.003 | -.019 | -.039 |
| SubSahAf | -.08 | -.14 | -.18 | -.20 | -.005 | -.003 | -.002 | -.001 | -.084 | -.143 | -.181 | -.198 |
| Brazil | -.07 | -.13 | -.17 | -.19 | -.002 | -.001 | .000 | .000 | -.077 | -.137 | -.176 | -.193 |
| OthLatAmer | .01 | .00 | -.01 | -.02 | .002 | .003 | .003 | .003 | .007 | .006 | -.002 | -.012 |
| | -.08 | -.16 | -.22 | -.26 | -.005 | -.004 | -.003 | -.002 | -.090 | -.166 | -0.223 | -0.260 |

|  | **Policy Scenario** |  |  |
|---|---|---|---|
|  | **Cap-and-Trade** | **RFS-Full** | **CaT+RFS** |
| Intercept | -0.00022** | -0.00001** | -0.00023** |
| GDP/capita | 0.00000 | 0.00000 | 0.00000 |
| **Export Share** |  |  |  |
| Oil | -0.00129 | 0.00002 | -0.00127 |
| Ag Commodities | -0.00268** | 0.00014*** | -0.00256** |
| **Import Share** |  |  |  |
| Oil | 0.00676** | 0.00014** | 0.00699*** |
| Ag Commodities | -0.00413* | -0.00021*** | -0.00442** |

*** indicates $p<0.01$; ** = $p<0.05$; * = $p<0.1$

Table 5.6: Decomposition of Welfare Effects by Commodity Trade Patterns

in the U.S. by almost 1 percentage point above what was projected under a cap-and-trade scenario. While seemingly small, the total CaT welfare loss for the U.S. in 2034 was only 0.6% of GDP, suggesting that the addition of the biofuel policy switches the welfare loss to a welfare gain of 0.4% of GDP. This gain however, appears to come at the expense of other regions, such as MidEastNA, SubSahAf, and nation's in Brazil which experience large reductions in welfare under the dual policy (1-2% of GDP). This is likely attributable to the fact that these regions tend to be both large fossil fuel exporter and agricultural importers, and are therefore susceptible to the adverse consequences of both U.S. policies.

## 5.6 Discussion and Conclusions

It is well documented that policies can compete with each other, creating unintended consequences or reducing their efficacy. In this case, the Renewable Fuel Standard (RFS) and cap-and-trade programs for carbon emissions (C&T) compete for bioenergy crops to meet different objectives, creating potential for competition that could influence the impacts of either program. In terms of broader market impacts, the interaction of the RFS and C&T place an additional burden on U.S. agricultural land resources, since both increase

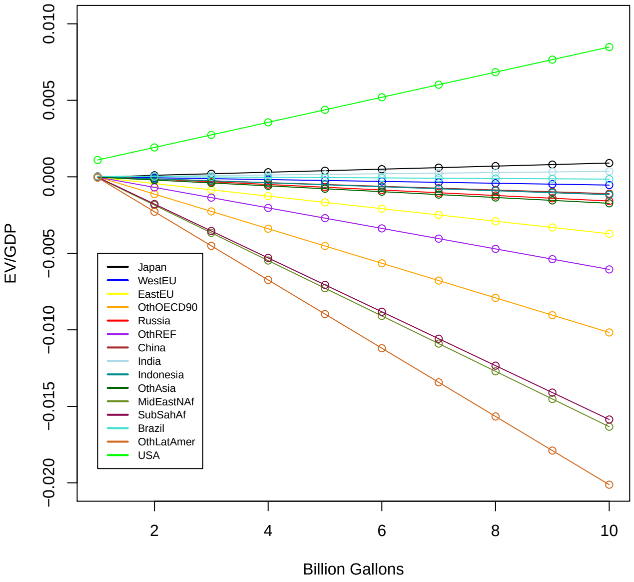

Figure 5.11: Projected Welfare Effects from Increasing Cellulosic Biofuel Mandate

demand for biomass. As competition for land from all economic sectors increases, broader market impacts will become more apparent. This will result in added pressure to expand total cropland both domestically and internationally. Agricultural commodity price increases that were observed just with RFS implementation will be exacerbated as marginal cropland becomes increasingly scarce.

Policy-induced competition for biomass between the electricity and transportation sectors will increase the cost of achieving the policy objectives set forth in both policies. Economy-wide, market-based greenhouse gas policies favor the use of biomass for electricity production rather than renewable transportation fuels, and electricity markets have more flexibility to respond to competition than transportation since they can turn to alternative low-carbon energy technologies such as wind, solar, and potentially natural gas. Therefore, the cost of competition is likely to be higher for the RFS, which creates a perfectly inelastic demand curve for biofuel. Cofiring biomass in existing coal-fired power plants, for example, requires little additional capital cost since there is already an extensive infrastructure in place in the United Stated. Biomass cofiring is also a proven technological process and is not subject to the cost uncertainties of an emerging industry, such as cellulosic biomass refining.

As was discussed in Chapter 4, there are numerous uncertainties that could affect the magnitude of these results. One important factor may be the degree to which the cellulosic refining industry experiences "learning-by-doing" (LBD) effects, which drive down unit production costs over time (McDonald and Shrattenholzer, 2002). Chen and Khanna (2012) show that the U.S. corn ethanol industry has experienced LBD effects on par with other renewable energy technologies. It is too early to evaluate the LBD effects for both the advanced biomass and cellulosic refining sectors; however, if the industry's experience is similar to other energy sectors, this could decrease the social costs of bioenergy policy interactions. LBD effects in the biomass industry could also increase land-use efficiency and mitigate some of the broader adverse markets effects resulting from land scarcity. A second important source of uncertainty is the future of domestic natural gas production in the United States. Natural gas has approximately half the carbon content as coal and is therefore a potentially critical abatement technology, especially in the short-run. The recent discovery of low-cost natural gas reserves in the U.S. would shift near-term GHG abatement out of the renewable energy sector. The simple passage of time erodes a key advantage for the bioelectricity sector, which is the ability to capitalize on the sunk infrastructure cost of coal-fired electric power plants. If low natural gas prices reduce the economic viability of bioelectricity production, any increase in biomass prices due to the RFS are likely to be less consequential from a GHG mitigation perspective. Renewable transportation fuel from cellulosic biomass may then become a more attractive long-run greenhouse gas mitigation option.

The results of this chapter are consistent with the broader theme of this dissertation. Namely, that bioenergy policies that aggressively mandate the use of land for conventional and cellulosic biomass production are likely to induce unintended consequences in agricultural and energy commodity markets. Increased competition for land potentially decreases the environmental benefits of bioenergy production. This outcome is unique to the bioeconomy since land is fixed in the long run, while substitution towards other inputs in essentially implausible. An "all-of-the-above" clean energy policy, often touted in federal and state policy debates, is less likely to be effective with bioenergy due to this land scarcity.

Many of the findings presented throughout this dissertation have highlighted the potential costs of bioenergy production and policy in the United States. However, accurate policy and welfare analysis also requires a full accounting of the benefits provided by bioenergy. Comprehensive analysis that incorporates both costs and benefits, at a domestic and global scale, is a challenging yet important area of future research. The economy-wide market-mediated impacts of bioenergy production studied in this dissertation are a result of land scarcity and competition. However, such scarcity also provides strong incentives for economic innovation. Continued innovation throughout the bioeconomy will be an essential component for improving both the environmental and economic calculus of bioenergy as a clean energy pathway in a carbon-constrained economy.

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# Appendix A

# FARM Biofuel Module

## Production Structure in FARM Biofuel Module

Figure A.1 shows the assumed production structure for conventional and advanced biofuels and cellulosic feedstocks. It is assumed that household do not directly consume biofuels but instead consume refined gasoline blend of petroleum and biofuel. As a result, figure A.1 also shows the final demand for all biofuel and cellulosic feedstock sectors.

The structural equations used in FARM are shown below. They include unit costs for each nest in the production structure, as well as input demand functions for the fuel-composite, conventional ethanol, and cellulosic biofuel sectors. Additional input demand functions are use for each additional nest but are not presented here for simplicity.

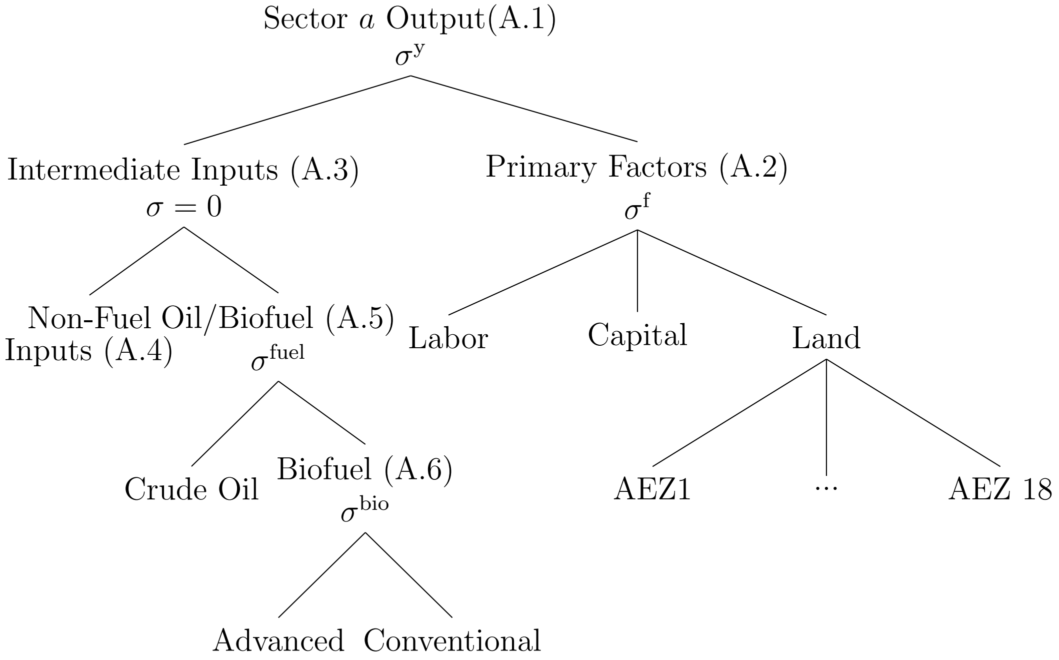

Figure A.1: Production Structure for Sector Input Demand in FARM Biofuel Module

Following Rutherford (2002), the unit cost functions for each nest can be specified as:

$$c^{\mathrm{y}}_{a,r}(\cdot) = \left[\theta^{\mathrm{i}}_{a,r}(c^{\mathrm{i}}_{a,r}(\cdot))^{1-\sigma^{\mathrm{y}}} + \theta^{\mathrm{f}}_{a,r}(c^{\mathrm{f}}_{a.r}(\cdot))^{1-\sigma^{\mathrm{y}}}\right]^{\frac{1}{1-\sigma^{\mathrm{y}}}} \tag{A.1}$$

$$c^{\mathrm{f}}_{a.r}(\cdot) = \left[\sum_{\mathrm{f}} \theta^{\mathrm{f}}_{f,a,r}(p^{\mathrm{f}}_{f,a,r})^{1-\sigma^{\mathrm{f}}}\right]^{\frac{1}{1-\sigma^{\mathrm{f}}}} \tag{A.2}$$

$$c^{\mathrm{i}}_{c,a,r}(\cdot) = \theta^{\mathrm{nonfuel}}_{c,a,r} * c^{\mathrm{nonfuel}}_{c,a,r}(\cdot) + (1 - \theta^{\mathrm{nonfuel}}_{c,a,r}) * c^{\mathrm{fuel}}_{c,a,r}(\cdot) \tag{A.3}$$

$$c^{\mathrm{nonfuel}}_{c,a,r}(\cdot) = \left[\theta^{d}_{c,a,r}(p^{\mathrm{d}}_{c,a,r})^{1-\sigma^{\mathrm{d}}_{c}} + (1-\theta^{\mathrm{d}}_{c,a,r})(c^{\mathrm{m}}_{c,a,r}(\cdot))^{1-\sigma^{\mathrm{d}}_{c}}\right]^{\frac{1}{1-\sigma^{\mathrm{d}}_{c}}} \quad \text{for (non-transportation fuels)} \subset c \tag{A.4}$$

$$c^{\mathrm{fuel}}_{c,a,r}(\cdot) = \left[\theta^{\mathrm{crude}}_{c,a,r}(p^{\mathrm{d}}_{\text{`oil'},a,r})^{1-\sigma^{\mathrm{fuel}}_{c}} + (1 - \theta^{\mathrm{crude}}_{c,a,r}(c^{\mathrm{bio}}_{c,a,r}(\cdot))^{1-\sigma^{\mathrm{fuel}}_{c}}\right]^{\frac{1}{1-\sigma^{\mathrm{fuel}}_{c}}} \quad \text{for (oil, biofuels)} \subset c \tag{A.5}$$

$$c^{\mathrm{bio}}_{c,a,r}(\cdot) = \left[\theta^{\mathrm{bio}}_{c,a,r}(p^{\mathrm{d}}_{\text{`eth'},a,r})^{1-\sigma^{\mathrm{bio}}} + (1 - \theta^{\mathrm{bio}}_{c,a,r})(p^{\mathrm{d}}_{\text{`cellbio'},a,r})^{1-\sigma^{\mathrm{bio}}}\right]^{\frac{1}{1-\sigma^{\mathrm{bio}}}} \quad \text{for (all biofuels)} \subset c \tag{A.6}$$

with the associated derived input demand functions for the fuel and biofuel composite:

$$q^{\mathrm{fuel}}_{c,a,r} = \bar{q}^{\mathrm{fuel}}_{c,a,r}\left(\frac{1}{\phi_{c,a,r}}\right)\left(\frac{\bar{p}^{\mathrm{fuel}}_{c,r} * c^{\mathrm{fuel}}_{c,a}}{p^{\mathrm{fuel}}_{c,r}}\right)^{\sigma^{\mathrm{fuel}}}\left(\frac{c^{y}_{a,r}}{c^{\mathrm{fuel}}_{a,r}}\right)^{\sigma^{y}} \quad \text{for (oil, biofuels)} \subset c \tag{A.7a}$$

$$q^{\mathrm{bio}}_{c,a,r} = \bar{q}^{\mathrm{bio}}_{c,a,r}\left(\frac{1}{\phi_{c,a,r}}\right)\left(\frac{\bar{p}^{\mathrm{bio}}_{c,r} * c^{\mathrm{bio}}_{c,a,r}}{p^{\mathrm{bio}}_{c,r}}\right)^{\sigma^{\mathrm{bio}}}\left(\frac{c^{fuel}_{c,a,r}}{c^{\mathrm{bio}}_{c,a,r}}\right)^{\sigma^{\mathrm{fuel}}}\left(\frac{c^{y}_{a,r}}{c^{\mathrm{fuel}}_{c,a,r}}\right)^{\sigma^{y}} \quad \text{for (all biofuels)} \subset c \tag{A.7b}$$

### Assumptions for Creating New Sectors

New GTAP sectors are created for the FARM biofuel module using the Splitcom program (Horridge, 2005). Cost of production data reviewed in section 4.2.2 along with base year production levels were used to create three new sectors for advanced biofuel production: switchgrass, corn stover, and cellulosic biofuel. An additional sector, cornb, was created so that stover could be produced by a subset of the primary corn sector as a byproduct. This sector has an identical production and demand structure to the original corn sector. Based on a review of the literature, stover value accounts fro approximately 17.5% of the value for a joint corn-stover operation. Cornb is therefore 3.7 times larger than the stover sector in the base year. Tables A.1 and A.2 show a summary of the cost shares. For all four new sectors, base year values were made as low as possible to reflect the fact that there is was no commercial production of cellulosic feedstocks and fuels. Table A.3 shows the base year production levels of the new sectors (and conventional ethanol), decomposed by unit price and quantity.

Table A.1: Corn Stover and Switchgrass Production Cost Shares

| | Maize | Switchgrass | Corn Stover |
|---|---|---|---|
| Primary Factors | | | |
| Labor | 19% | 9% | 20% |
| Land | 13.8% | 3.6% | 0.0% |
| Capital | 16.8% | 40% | 27% |
| Intermediate Inputs | | | |
| Fertilizer/Chemicals | 13% | 21.5% | 25% |
| Fuel | 3.5% | 2.8% | 10% |
| Transport | 2.9% | 18.3% | 18% |
| Establishment/Seed | 1.0% | 2.5% | - |
| Services | 16% | - | - |
| Other | 14% | 2.3% | - |

Table A.2: Biorefinery Production Cost Shares

| | Conventional Ethanol[1] | Cellulosic Biofuel[2] |
|---|---|---|
| Primary Factors | | |
| Labor | 3% | 5% |
| Capital | 35% | 26.79% |
| Intermediate Inputs | | |
| Corn | 40% | - |
| Cellulosic Biomass | - | 36.44% |
| Electricity | 12% | 5% |
| Enzymes | 8% | 12% |
| Other[3] | 2% | 14.77% |

[1] Fuel yield = 348 liters ethanol per dry ton of feedstock. Break-even price: \$0.43/liter (\$1.62/gallon).

[2] Fuel yield = 215 liters biogasoline per dry ton of feedstock. Break-even price: \$0.84/liter (\$3.17/gallon).

[3] Other costs include additional business services, refinery construction, and waste disposal.

Table A.3: Base Year Production Assumptions for Cellulosic Biofuel Sectors (\$2004)

| | Conventional Ethanol[1] | Cellulosic Biofuel[1] | Corn Stover[2] | Switchgrass[2] |
|---|---|---|---|---|
| Quantity[1 2] | 2.27 | 0.01 | 105.6 | 70.183 |
| Price (2004\$/unit) | \$2.22 | \$3.17 | \$54.71 | \$82.31 |
| Value of Production (\$ million) | \$5,040 | \$31.715 | \$5.777 | \$5.777 |

[1] billion gallons of gasoline equivalent (bgge)

[2] thousand metric tons

The final demand structure for advanced biofuel production assumes that cellulosic feedstocks have no alternate use outside of cellulosic biofuel production. Cellulosic biofuel is used entirely by the the refined petroleum sector as an intermediate input. Taheripour et al. (2011b) assumes that 75% of all biofuel supply is used as an intermediate input into the refined petroleum sector, while the remaining 25% is consumed directly by households. This assumption does not seem appropriate for the United States at the present time since the current vehicle fleet presents no options for consumers to differentiate between fuel types (except for a small fraction who use flex-fuel vehicles). Our simplification also eliminates the need to determine a price elasticity of demand for biofuel consumption for households, thereby reducing the number of assumptions in the model.

This study assumes that there is no international production or trade of cellulosic biofuels and feedstocks. Aggressive cellulosic biofuel mandates in the European Union suggests that there will be future international production; however, the objective of this study is to isolate the impact of the U.S. cellulosic mandate. Because of this assumption, trade elasticities for cellulosic biofuel are not required.

Elasticities for the new biofuel nesting structure are set to reflect several important assumptions. In the CES production structure, input substitution elasticities between zero and one imply that the inputs are complements. Elasticities of one imply that the inputs are used in fixed proportions. Elasticities greater than one imply that the inputs are substitutes. For A.5, biofuel and crude oil are assumed to be imperfect substitutes, with $\sigma^{fuel} = 3.95$, following Hertel et al. (2008). $\sigma^{bio}$ (specified in A.6) is set to 1, which reflects the assumption that under a separate, binding mandate for both conventional and cellulosic biofuels, the petroleum blending sector cannot substitute between the two fuel types based on relative biofuel price changes. If cellulosic biofuel production becomes cost competitive with conventional ethanol and/or exceeds the mandated quantities, this assumption should be relaxed to allow for gasoline blenders to choose the lowest cost fuel source. All remaining elasticities are set to the GTAP default values.

The GTAP land use data must also be modified to incorporate switchgrass production. Aggregate land use for switchgrass in the U.S. is divided amongst the agro-ecological zones under the assumption that land suitable for growing wheat is also suitable for growing switchgrass. The base year assumptions detailed in table A.3 shows that 70,183 metric tons of switchgrass are produced initially. With an average yield of 8.11 tons/ha, an initial acreage of 8,654 hectares of land is used in the base year for switchgrass production. Table A.4 shows the acreage and value breakdown across AEZs in the base year. The base year land assumptions for switchgrass should not have a significant impact on simulation results, but are necessary in order to calibrate the model.

Table A.4: Base Year Land Value Shares and Acreage for Switchgrass

| | Land Value Shares | Acreage (ha) |
|---|---|---|
| AEZ1-6 | 0% | 0 |
| AEZ7 | 31.5% | 3,053 |
| AEZ8 | 25.9% | 2,429 |
| AEZ9 | 10.5% | 971 |
| AEZ10 | 15.5% | 1,054 |
| AEZ11 | 11.2% | 711 |
| AEZ12 | 3.5% | 251 |
| AEZ13 | 1.6% | 158 |
| AEZ14 | 0.3% | 24 |
| AEZ15-18 | 0% | 0 |
| Total | 100% | 8,654 |