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Essays concerning the cellulosic biofuel industry

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by

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DEDICATION

I would like to dedicate this thesis to my husband Eric. Your unconditional love and support, even in my crazy moments, made this journey attainable. Never will I be able to thank you enough.

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LIST OF ACRONYMS

bgy	Billion gallons per year
BioBreak	The Biofuel Breakeven program
Btu	British thermal units
CAAA	Clean Air Act Amendments
CAFE	Corporate Average Fuel Economy
CHST	Biomass collection, harvest, storage, and transportation
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
DOE	U.S. Department of Energy
dt	Dry ton
E10	Fuel blend with (up to) 10% denatured ethanol
E15	Fuel blend with (up to) 15% denatured ethanol
E85	Fuel blend with (up to) 85% denatured ethanol
EIA	U.S. Energy Information Agency
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act
gal	Gallon
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
Gt	Green ton
HEC	Herbaceous energy crops
LCA	Life-cycle analysis
mgy	Million gallons per year
mpg	Miles per gallon
mt	Metric ton
MSW	Municipal solid waste
MTBE	Methyl tertiary butyl ether
NASS	National Agricultural Statistics Service
OPEC	Organization of Petroleum Exporting Countries
RFS	Renewable Fuels Standard
RFS2	Revised Renewable Fuels Standard
SRWC	Short rotation woody crops
VEETC	Volumetric Ethanol Excise Tax Credit

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CHAPTER 1. GENERAL INTRODUCTION

1.1 Overview

Interest in the development of a U.S. cellulosic biofuel industry has been motivated by the concepts of energy security and independence, rural development opportunities, and environmental benefits associated with substituting biofuel for fossil fuels. Current policy support for industry development includes both market-based incentives and mandates.

The 2008 Farm Bill established market-based incentives in the form of subsidies to biomass suppliers and a tax credit to cellulosic biofuel processors. Further, the revised Renewable Fuel Standard (RFS2) outlined in the 2007 Energy Independence and Security Act mandates the use of increasing volumes of cellulosic biofuel between 2010 and 2022.

Despite policy incentives, the industry has been slow to develop. Cellulosic biofuel production is currently limited to research labs and pilot plants. Without a commercial-scale biomass supply system or cellulosic biorefinery, knowledge is limited regarding the costs and environmental impacts of cellulosic biofuel production at the scale needed to meet current and future mandate levels.

For this reason, economists and environmentalists have been tasked with evaluating potential economic and environmental implications of biofuel expansion.[1] Yet, understanding the economic implications of biofuel expansion first requires an understanding of the economics of cellulosic biofuel production. The objective of my dissertation is to provide a better understanding of the economics of cellulosic biofuel production and identify important economic trade-offs that will be encountered in the development of a cellulosic biofuel industry.

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[1] For example, the National Research Council (NRC, 2011) commissioned the Committee on Economic and Environmental Impacts of Increasing Biofuels Production to evaluate the potential economic and environmental effects of U.S. biofuel policy with focus on the RFS2 mandates.

1.2 Dissertation organization

The dissertation is organized into three main chapters. Chapter 2 provides a general introduction to cellulosic biofuel. A historical account of the biofuel industry details events that led to former and current policy support. A brief overview of first-generation biofuels is accompanied by a discussion of the shift towards second-generation biofuels, including cellulosic biofuel. Potential cellulosic biofuel feedstocks are identified along with the potential contribution from biomass to the energy sector. The chapter concludes with the current status of second-generation technology and a discussion of challenges facing industry development.

Although each chapter can be read independently as these are largely self-contained, Chapter 2 provides useful background information for the model formulation and empirical analysis in Chapters 3 and 4.

Chapter 3 considers the economics of cellulosic biofuel production. Breakeven models of the local feedstock supply system and biofuel refining process are constructed to develop the Biofuel Breakeven (BioBreak) program. BioBreak is a stochastic, Excel-based program that evaluates the feasibility of local biofuel and biomass markets under various policy and market scenarios. Program results indicate whether a cellulosic biofuel market is economically sustainable, and if not, provides market conditions needed to sustain the local market.

An application of the BioBreak program is presented using expected market conditions for 14 local cellulosic biofuel markets that vary by feedstock and location. For the 14 markets considered, long-run cellulosic ethanol production is not sustainable without significant policies to support the industry or long-run oil prices of $135 – $170 per barrel. The economic costs of biofuel production identified from the BioBreak application are higher than frequently anticipated[2] and raise questions

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[2]A subset of the literature that falls within this category includes: Aden (2008), Aden et al. (2002), Brechbill & Tyner (2008a), Brechbill & Tyner (2008b), de La Torre Ugarte et al. (2003),Epplin & Haque (2011), Epplin et al. (2007), Graham et al. (2007), Huang et al. (2009), Khanna & Dhungana (2007), Mapemba et al. (2007), Mapemba et al. (2008), McLaughlin et al. (2002), McLaughlin et al. (2006), Perlack & Turhollow (2002),

about the potential of cellulosic ethanol as a sustainable and economical substitute for conventional fuels.

Chapter 3 concludes by extending BioBreak program results using life-cycle analysis to derive the per unit cost of carbon savings from substituting cellulosic ethanol for conventional transportation fuel. This carbon price represents the value of reduced emissions implied by government intervention in the cellulosic ethanol industry, such as the RFS2 mandates. Based on current market conditions, policies that sustain cellulosic ethanol production are found to value a reduction in carbon equivalents between $141 and $280 per metric ton, higher than most carbon tax rates or prices discussed in the literature.[3]

Chapter 4 evaluates the economic trade-offs in commercial-scale cellulosic biofuel production that result from spatial variation in potential biomass supply, including landowner behavior. A long-run biomass production through bioenergy conversion cost model is developed that incorporates heterogeneity of biomass suppliers within and between local markets. The model builds on previous literature by treating biomass as a non-commoditized feedstock and relaxes the common assumption of fixed biomass density and price within local markets.

An empirical application is provided for U.S. switchgrass-based ethanol. A unique dataset of offers to enroll in the Conservation Reserve Program (CRP) are used to identify revealed opportunity cost of potential biomass cropland within local markets. Cost-minimizing biofuel production decisions – including biorefinery size, biomass transportation distance, and price of biomass – are found to vary significantly across locations. Local biofuel supply estimates are used to evaluate economic trade-offs in biofuel expansion, as well as the potential for and costs to meet the RFS2 cellulosic biofuel mandates. Empirical results indicate spatial variation in the economics of biomass

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Perlack & Turhollow (2003), Petrolia (2008), Popp & Hogan (2007), Sheehan et al. (2004), Vadas et al. (2008), and Wallace et al. (2005).

[3]See Baker et al. (2010), Brechbill & Tyner (2008b), de la Torre Ugarte et al. (2009), EPA (2006), Gomes & Araujo (2009), Johnson (2006), Khanna (2008), Murray et al. (2005), Parry & Small (2005), and Updegraff, Baughman, & Taff (2004).

production plays an important role in the potential supply and distribution of U.S. cellulosic biofuel production, and assuming fixed local biomass supply conditions leads to an over- or under-estimate of potential biofuel supply.

CHAPTER 2. CELLULOSIC BIOFUEL: AN OVERVIEW OF THE POLICIES, POTENTIAL, AND CHALLENGES

"Advanced biofuels are a key component of President Obama's 'all-of-the-above' energy strategy to limit the impact of foreign oil on our economy and take control of our energy future."

- *U.S. Agriculture Secretary Tom Vilsack (USDA, 2012)*

2.1 Introduction

In the wake of unstable energy prices and rising environmental concerns, biofuels as an alternative transportation fuel has drawn considerable attention. While interest has grown in recent years, the idea of biofuel as an alternative transportation fuel is not new. This chapter begins with a historical account of the biofuel industry focusing on the events that led to former and current policy support. Next, a brief overview of first-generation biofuels is accompanied by a discussion of the shift towards second-generation biofuels including cellulosic biofuel. Potential cellulosic feedstocks are identified along with the potential contribution from biomass to the energy sector. These discussions are followed by an overview of the current status of second-generation technology. The chapter concludes with a discussion of policy uncertainty and other challenges facing the cellulosic biofuel industry.

2.2 Historical background

The concept of ethanol as an alternative transportation fuel dates back to the 1800s. Earlier inventors such as Samuel Morey and Nicholas Otto experimented with the use of ethanol for internal combustion engines,[4] but it was Henry Ford's Model T in 1908 that revolutionized the use of ethanol as a transportation fuel. Considered the first affordable automobile, the Ford Model T contained a flexible-fuel engine capable of running on pure ethanol, gasoline, or a combination referred to as

[4] Samuel Morey developed an engine capable of running on ethanol and turpentine in 1826. Nicholas Otto used ethanol to fuel one of his engines in 1860 (U.S. EIA, 2008b).

gasohol (Model T, 2012; Solomon, Barnes, & Halvorsen, 2007).[5] Henry Ford was well known for his outspoken support for farm- and waste-based fuels. He provided his biofuel vision in a 1925 New York Times interview (Ford Predicts Fuel from Vegetation, 1925):

> *"The fuel of the future is going to come from fruit like that sumac out by the road, or from apples, weeds, sawdust – almost anything. There is fuel in every bit of vegetable matter that can be fermented. There's enough alcohol in one year's yield of an acre of potatoes to drive the machinery necessary to cultivate the fields for a hundred years."*

The ability of ethanol to provide a homegrown, renewable substitute for petroleum-based fuel wasn't its only attractive characteristic. Ethanol is an anti-knock agent or octane enhancer and provides improved engine operation even at low blend levels.

Fuel demand during World War I boosted the U.S. ethanol industry to 50 – 60 million gallons per year (mgy) (U.S. EIA, 2008). Despite prohibition and discovery of tetraethyl lead as an alternative and less expensive anti-knock agent, the industry survived the 1920s and 1930s. Ethanol's competitiveness with lead-based gasoline was aided during the mid-1930s by lower corn prices (DiPardo, 2000; Solomon, Barnes, & Halvorsen, 2007). Increased fuel demand during the Second World War helped maintain ethanol demand even though most ethanol was allocated to non-war activities. Following World War II, the use and interest in ethanol faded. New oil discoveries provided an abundant supply of cheap leaded gasoline and reduced pressure to find petroleum substitutes (Solomon, Barnes, & Halvorsen, 2007). Between the late 1940s and late 1970s, commercial ethanol production was effectively non-existent in the United States.

Rapid growth in energy demand diminished the abundant supply of cheap petroleum-based fuels by the early 1970s. Between 1970 and 1973, the market price of oil doubled and oil shortages appeared in many industrialized countries, including the United States (Duffield, Xiarchos, & Halbrook, 2008). A worldwide energy crisis was triggered in October 1973 as the Arab members of

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[5] Henry Ford's first vehicle, the Ford Quadricycle, also featured an ethanol-powered engine (Goettemoeller & Goettemoeller, 2007; Doeden, 2007).

OPEC[6] tightened oil supplies and embargoed the United States. Lines formed at refueling stations across the United States and retail prices increased forty percent (Duffield, Xiarchos, & Halbrook, 2008). The embargo was lifted in March 1974 and oil supplies were quickly restored. The relief was temporary. A second energy crisis developed in late 1978 as the Iranian Revolution disrupted world oil supplies. With the events of the first energy crisis still fresh in memory, widespread panic buying led to the return of long lines at refueling stations and a thirty percent increase in the retail price of gasoline (Duffield, Xiarchos, & Halbrook, 2008). The energy crises of the 1970s revealed the United States' growing dependence on foreign oil and renewed interest in finding alternatives for petroleum-based fuels.

Around the same time, environmental concerns emerged over the use of lead-based additives in gasoline (DiPardo, 2000). In 1973, the Environmental Protection Agency (EPA) announced a required phase-out of lead in all grades of gasoline (U.S. EPA, 1973). Demand for alternative gasoline additives increased, but ethanol was not the primary additive used during this time period. Methyl tertiary butyl ether (MTBE) dominated most oxygenated gasoline markets until the mid-1990s due to better blending characteristics and lower costs (U.S. EPA, 2008; Solomon, Barnes, & Halvorsen, 2007). Ethanol was largely limited to Midwest markets where transportation from the production facility to final use was relatively low (DiPardo, 2000).

The first U.S. ethanol subsidy program began in 1978 through the Energy Tax Act. The Energy Tax Act established a federal excise tax exemption equivalent to $0.40 for every gallon of blended ethanol. Several states followed suit by exempting ethanol from state-level gasoline excise taxes (DiPardo, 2000). The 1978 Energy Tax Act also introduced the first official definition of gasohol as any blend of gasoline with at least 10 percent non-fossil fuel-based ethanol by volume. Ethanol production in the United States, which was virtually non-existent 10 years prior, responded to

[6] Organization of Petroleum Exporting Countries

increased demand and policymakers' incentives and reached almost 175 million gallons by 1980 (RFA, 2012).

A series of policies enacted by Congress in the early 1980s helped accelerate industry growth. Congress' support for biofuels during this time period is nicely summarized in the 1980 Energy Security Act[7]:

> "The Congress finds that –
>
> (1) the dependence of the United States on imported petroleum and natural gas must be reduced by all economically and environmentally feasible means, including the use of biomass energy resources; and
>
> (2) a national program for increased production and use of biomass energy that does not impair the Nation's ability to produce food and fiber on a sustainable basis for domestic and export use must be formulated and implemented within a multiple-use framework."

In keeping with these findings, the 1980 Energy Security Act outlined price guarantees for biomass energy projects and offered small ethanol producers, classified as producers of less than 1 mgy, up to $1 million in loan guarantees. Further, Congress passed the Gasohol Competition Act of 1980 to prohibit discrimination by oil companies against the sale of gasohol.[8] The Crude Windfall Tax Act of 1980 extended the excise tax credit of $0.40 per gallon ethanol volume, and subsequently increased to $0.50 and then to $0.60 per gallon of blended ethanol in 1982[9] and 1984[10], respectively. To avoid subsidizing foreign ethanol suppliers, Congress placed an offsetting tax (i.e., tariff) on imported ethanol. These policy incentives, together with high oil prices during the First Persian Gulf War, prompted investment in the ethanol industry during the early 1980s.

Production plateaued in the mid-1980s as oil prices returned to their pre-shock levels (see Figure 2.1). Despite subsidization, only 74 of the 163 ethanol plants constructed (45%) remained in

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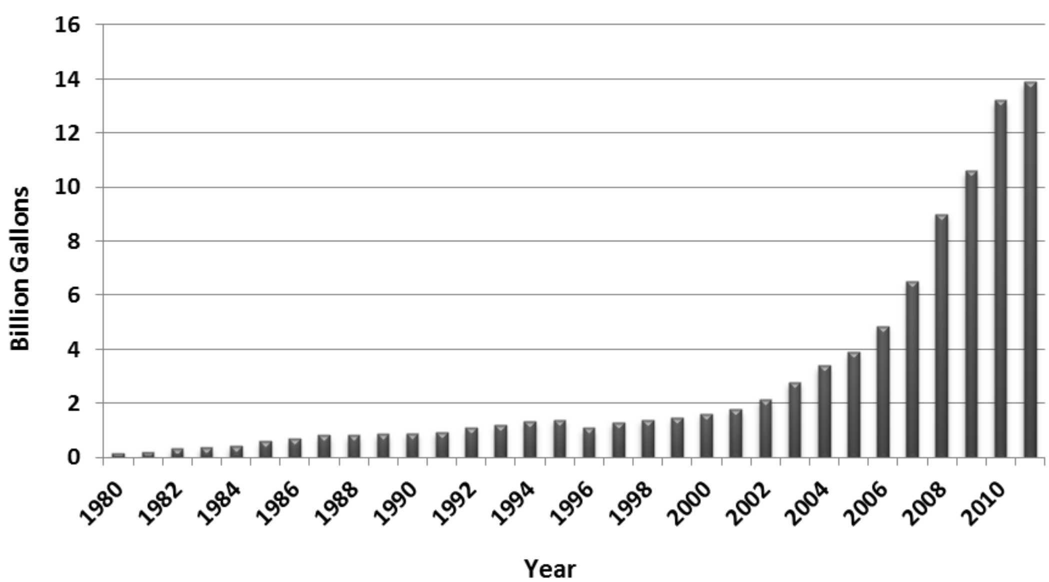
[7]These findings are outlined within the Biomass Energy and Alcohol Fuels Act of 1980, one of six acts within the 1980 Energy Security Act.
[8]The Gasohol Competition Act of 1980 is an amendment to the Clayton Act.
[9] Surface Transportation Assistance Act of 1982.
[10]Tax Reform Act of 1984.

operation by the end of 1985 (U.S. EIA, 2008b). In 1988, the Alternative Motor Fuels Act incentivized the production of flexible fuel vehicles by providing vehicle manufacturers Corporate Average Fuel Economy (CAFE) credits (U.S. EPA, 2011).[11] The Alternative Motor Fuels Act had little effect on actual biofuel use since few retailers at this time offered E85. The policy faced criticism as a way for automakers to avoid CAFE requirements (Solomon, Barnes, & Halvorsen, 2007; Duffield, Xiarchos, & Halbrook, 2008).

Figure 2.1 – U.S. ethanol production
(1980 – 2011)



Source: RFA. Historic U.S. fuel Ethanol Production. http://www.ethanolrfa.org/pages/statistics

In 1990, the ethanol tax credit was lowered to $0.54 per gallon of ethanol[12] – the value at which the credit would remain until 2001. Small ethanol producers, redefined as less than 30 mgy, benefited from an additional tax credit of $0.10 per gallon for the first 15 million gallons. The passage of the Clean Air Act Amendments (CAAA) in 1990 provided indirect support for the ethanol industry. Oxygenated fuel use was required for certain areas during winter months to reduce carbon monoxide emissions. Although ethanol was typically more expensive than MTBE, ethanol's higher

[11] Since 1975, vehicle manufactures have been required to meet minimum CAFE requirements based on a weighted average of the EPA fuel-efficiency ratings for its vehicles (Crandall, 1992).
[12] Omnibus Budget Reconciliation Act of 1990.

oxygen content relative to MTBE allowed ethanol to compete during winter months in oxygenate markets outside the Midwest (DiPardo, 2000).

Formal definitions for alternative fuel and alternative fuel vehicles were introduced in the Energy Policy Act of 1992 (EPAct 1992). Based on these definitions, federal and state vehicle fleets were required to contain at least 75% alternative fuel vehicles (U.S. EPA, 2011). An ethanol blend with at least 85 percent ethanol (E85) classified as an alternative fuel.[13] The EPAct 1992 provided tax deductions for consumer purchases of alternative fuel vehicles or vehicles made compatible with alternative fuels such as E85. The ethanol industry also achieved an important milestone in 1992 as production surpassed 1 billion gallons.

Despite previous investments and political support, industry survival was threatened in the mid-1990s as petroleum prices remained low and weak harvests escalated corn prices. State-level policies, particularly in the Midwest, helped sustain the struggling industry (Solomon, Barnes, & Halvorsen, 2007). Industry growth faltered in 1996 as production returned to 1992 levels. The setback was only temporary and the industry experienced continual growth for the subsequent 15 years (see Figure 2.1).

Ethanol demand expanded in the late 1990s and early 2000s as the gasoline additive MTBE faced environmental and health concerns. Traces of MTBE were found in groundwater supplies, prompting the EPA to issue a Drinking Water Advisory in December 1997. The EPA's recommendation in 2000 of a four-year national phase-out, along with state-level bans on MTBE use, increased demand for ethanol as a gasoline additive. By 2005, 25 states had adopted plans to partially or completely ban MTBE (U.S. EPA, 2007). The phase-out in 2004 and 2005 provided a significant boost for the ethanol industry (Babcock & Fabiosa, 2011).

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[13] The official minimum blend requirement to qualify as an alternative fuel based on the EPAct 1992 is as follows: "mixtures containing 85 percent or more (or such other percentage, but not less than 70 percent, as determined by the Secretary, by rule, to provide for requirements relating to cold start, safety, or vehicle functions) by volume of methanol, denatured ethanol, and other alcohols with gasoline or other fuels."

To reduce MTBE use, the Energy Policy Act of 2005 (EPAct 2005) eliminated the 1990 CAAA oxygenated fuel requirements (Solomon, Barnes, & Halvorsen, 2007; Duffield, Xiarchos, & Halbrook, 2008). This policy change had a minor impact on the ethanol industry compared to the introduction of the first Renewable Fuels Standard (RFS), also part of the EPAct 2005. The RFS required increasing annual volumes of renewable fuels to be blended with the U.S. transportation fuel supply between 2006 and 2012. The RFS required 7.5 billion gallons per year (bgy) by 2012, almost double the 4 billion gallons mandated for 2006. The primary biofuel used during this time period, and the biofuel projected to satisfy the majority of the RFS, was corn-based ethanol. The EPAct 2005 also modified the definition of ‘small ethanol producer’ from 30 to 60 mgy.

In 2007, the Energy Independence and Security Act (EISA) introduced a revised Renewable Fuels Standard (RFS2). The RFS2 expanded the RFS to include diesel, raised the annual renewable fuel requirements with increasing volumes up to 36 bgy by 2022, established subcategories of renewable fuels with separate sub-mandates, and required minimum greenhouse gas (GHG) reduction standards for each subcategory relative to 2005 gasoline or diesel (U.S. EPA, 2012). Given the significance of the RFS2, a more detailed description is provided in Box 2.1.

Box 2.1 – Revised Renewable Fuel Standard (RFS2)

The revised Renewable Fuels Standard (RFS2) outlined in the Energy Independence and Security Act of 2007 (EISA) mandates minimum blend volumes for conventional biofuel (i.e., corn ethanol) and advanced biofuel. The advanced biofuel mandate is subcategorized into cellulosic biofuel, biomass-based diesel, and undifferentiated advanced biofuel (see Table 2.1) (U.S. Congress, 2007). Figure 2.2 illustrates the breakdown of the RFS2 between conventional and advanced biofuel. Figure 2.3 shows the subcategory mandates that comprise the advanced biofuel mandate.

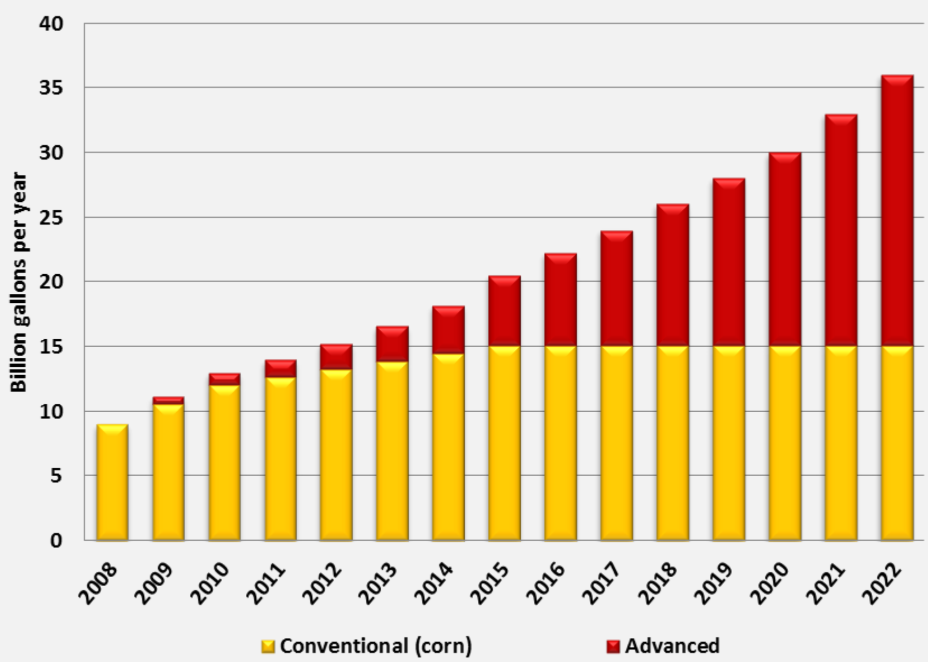
Beyond volume standards, each type of biofuel must satisfy a minimum GHG reduction standard, or low carbon fuel standard, relative to 2005 gasoline or diesel. Conventional biofuel from facilities built after December 19, 2007 must achieve a 20% GHG reduction. The conventional biofuel mandate is 13.2 billion gallons in 2012 and increases until 2015 when the mandate plateaus at 15 bgy through 2022. The cellulosic biofuel volume requirement increases from 100 million gallons in 2010 to 16 billion gallons in 2022 and must achieve at least 60% GHG reductions. One billion gallons of biomass-based diesel with at least a 50% GHG reduction is required for 2012. Biodiesel mandates for 2013 – 2022 are to be determined by the EPA but no less than 1 bgy. An additional 4 bgy of undifferentiated advanced biofuel, or any renewable fuel other than corn ethanol with at least 50% GHG reductions, is mandated for 2022 (U.S. EPA, 2010). If cellulosic biofuels are the most economical advanced biofuel, the cellulosic biofuel blending requirement could reach 20 billion gallons in 2022; 16 to meet the cellulosic biofuel mandate and 4 to meet the advanced biofuel mandate. Biodiesel and imported sugar-cane are other options to meet the undifferentiated advanced biofuel mandate as long as they meet the GHG reduction criterion.

Table 2.1: EISA RFS2 volume requirements (bgy)

Year	Conventional biofuel	Advanced biofuel			Total RFS2
		Cellulosic biofuel	Biodiesel	Undifferentiated	
2008	9	--	--	--	9
2009	10.5	--	0.50	0.1	11.1
2010	12	0.1	0.65	0.2	12.95
2011	12.6	0.25	0.8	0.3	13.95
2012	13.2	0.5	1	0.5	15.2
2013	13.8	1	--[a]	1.75[b]	16.55
2014	14.4	1.75	--	2	18.15
2015	15	3	--	2.5	20.5
2016	15	4.25	--	3	22.25
2017	15	5.5	--	3.5	24
2018	15	7	--	4	26
2019	15	8.5	--	4.5	28
2020	15	10.5	--	4.5	30
2021	15	13.5	--	4.5	33
2022	15	16	--	5	36

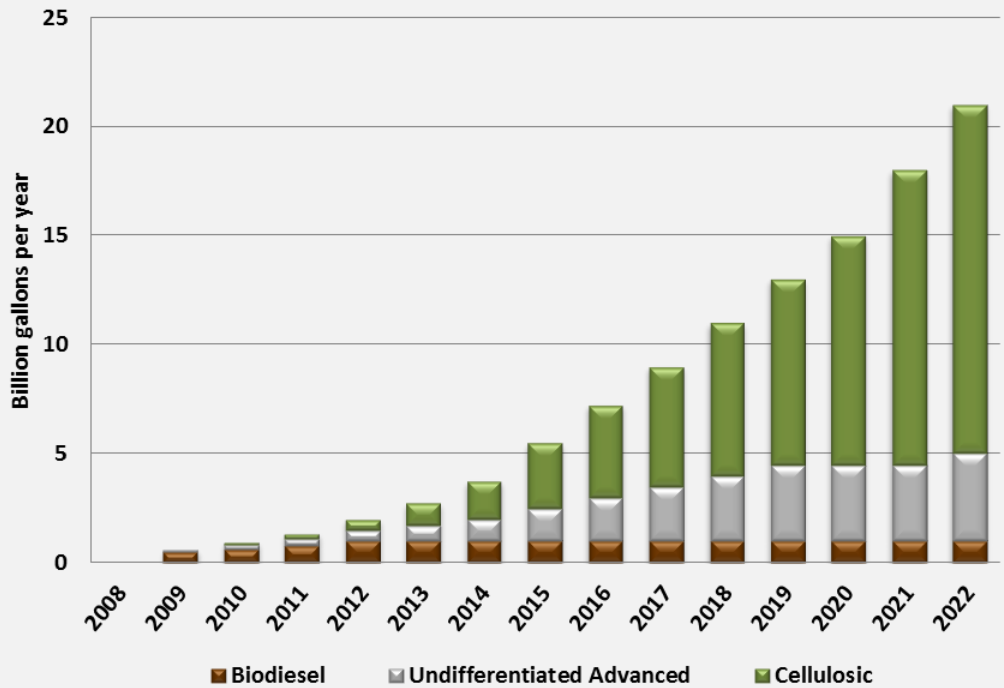
Source: U.S. EPA (2010c)
[a]Biodiesel levels between 2013 and 2022 to be determined by EPA but no less than 1.0 bgy.
[b] The undifferentiated volume requirements for 2013 – 2022 include the minimum 1.0 bgy of biodiesel.

Figure 2.2 – RFS2 mandates



Source: U.S. EPA (2010c)

Figure 2.3 – RFS2 advanced biofuel sub-mandates



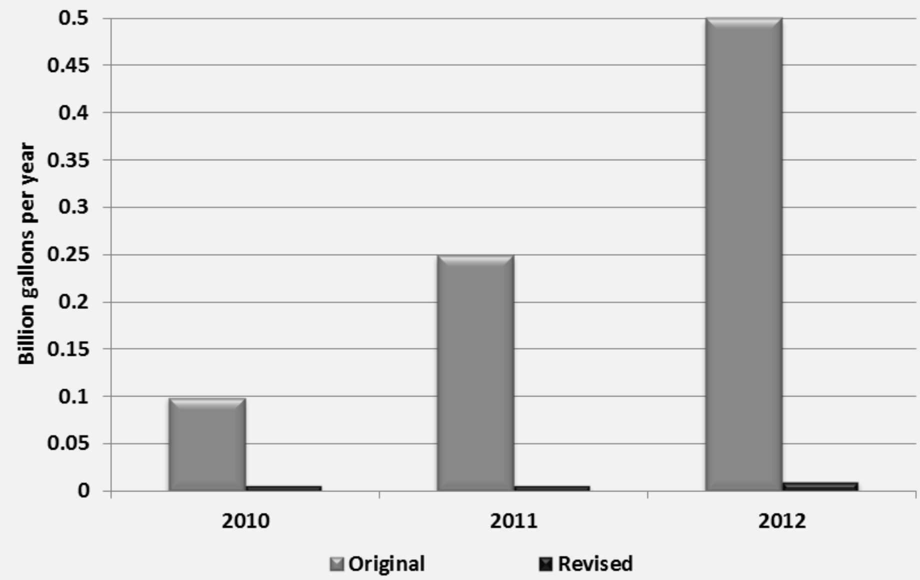
Source: U.S. EPA (2010c)

To monitor biofuel production, each gallon of renewable fuel has a category-specific renewable identification number (RIN) and obligated parties must provide RINs to satisfy their minimum blend requirements. Obligated parties consist of registered importers or refiners for gasoline or diesel. RINs can be acquired from production of renewable fuels or purchased from the RIN trading market. The trading market allows low-cost producers to produce above their blend requirements and sell excess RINs to obligated parties with relatively high production costs. Since a commercial scale cellulosic biorefinery does not exist, a cellulosic biofuel RIN market is currently non-existent (McPhail, Westcott, & Lutman, 2011).

Although the RFS2 provides explicit annual mandate quantities, revisions are allowed to prevent costly investment. The EPA conducts an annual evaluation of the cellulosic biofuel industry and the EPA Administrator waives a portion of cellulosic biofuel standards if deemed necessary. For example, the RFS2 required 500 million gallons of cellulosic biofuel production in 2012, but the EPA lowered the 2012 volume standard to 10.45 million ethanol equivalent gallons given industry projections (U.S. EPA, 2012a). Figure 2.4 shows the difference between the original and revised cellulosic biofuel mandates for 2010, 2011, and 2012.

When a portion of the cellulosic biofuel mandate is waived, the EPA is required to make cellulosic waiver credits available for purchase by obligated parties. Waiver credits can be used to meet the revised mandated volumes in lieu of blending cellulosic biofuel. Waiver credits are priced at the maximum of "(i). $0.25 per cellulosic biofuel waiver credit, adjusted for inflation in comparison to calendar year 2008; or (ii) $3.00 less the wholesale price of gasoline per cellulosic biofuel waiver credit, adjusted for inflation in comparison to calendar year 2008" (U.S. EPA, 2010b, p. 14892). The wholesale price of gasoline is determined by the average refiner's monthly bulk sale price over the previous 12 months as of September 30 prior to the compliance year. Waiver credits were available for \$1.56 per gallon in 2010 and \$1.13 per gallon in 2011 (U.S. EPA, 2010a; 2010b). The 2012 waiver credit price is significantly lower at \$0.78 per gallon (U.S. EPA, 2012a).

Figure 2.4 – RFS2 original vs. revised cellulosic biofuel mandates (2010 – 2012)

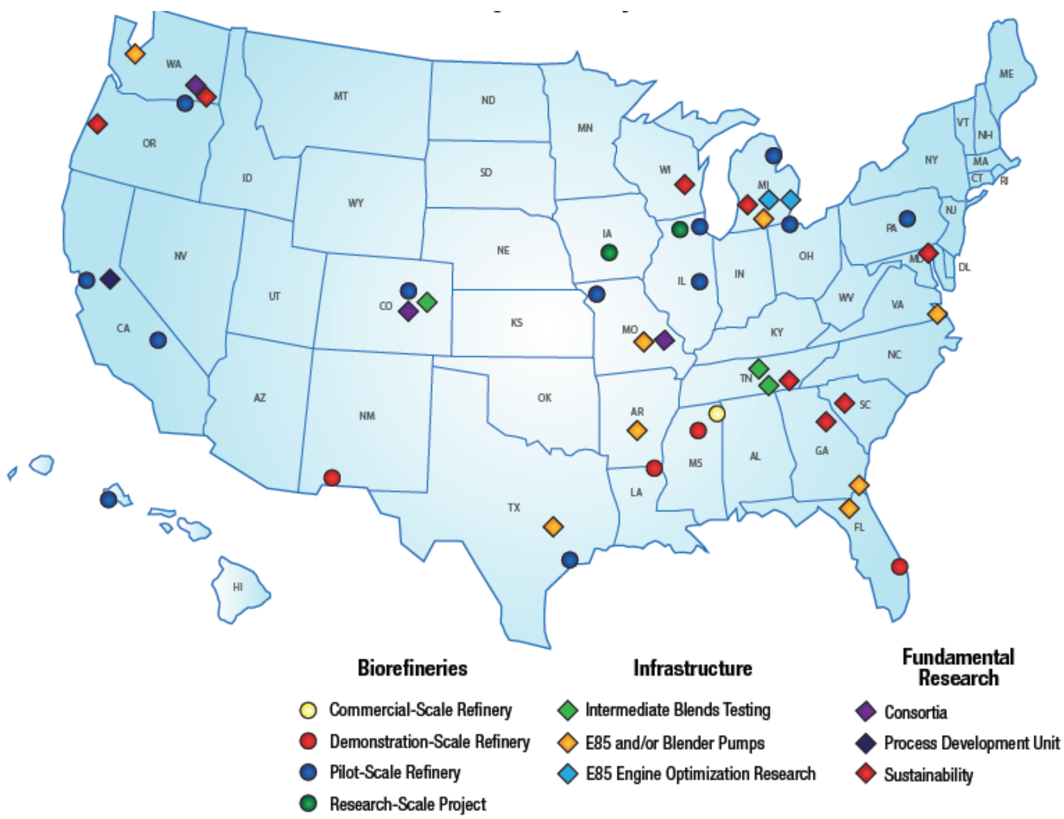


Source: U.S. EPA (2010a, 2010b,2012a)

The Food, Conservation, and Energy Act of 2008, commonly known as the 2008 Farm Bill, extended many of the programs authorized in previous legislation. Eleven programs were established for renewable energy, biobased products, and bioenergy including grants, loans, and loan guarantees for biorefineries (U.S. DOE, 2011b). Unlike previous legislation, the 2008 Farm Bill provided financial incentives specific to second generation or cellulosic biofuel production. Cellulosic biofuel producers qualify for a \$1.01 per gallon tax credit. Biomass suppliers benefit from two means of assistance provided by the Biomass Crop Assistance Program (BCAP): 1) dollar-for-dollar matching payments for collection, harvest, storage, and transportation up to \$45 per ton of feedstock and 2) up to 75% reimbursement for costs of perennial crop establishment (USDA - FSA, 2011).

Less than a year after the implementation of the 2008 Farm Bill, the American Reinvestment and Recovery Act of 2009 (Recovery Act) provided additional funding to support fundamental bioenergy research and the development of pilot, demonstration, and commercial-scale biorefineries. Locations and general categories for Recovery Act projects as of March 2010 are shown in Figure 2.5.

Figure 2.5 – *Recovery Act* projects as of March 2010



Source: US Department of Energy (2010).

While policy support for second generation biofuels expanded, the federal tax credit for conventional ethanol underwent several changes and reductions starting in 1990. The Omnibus Budget Reconciliation Act of 1990 reduced the tax credit from $0.60 per gallon to $0.54 per gallon of ethanol. In 1998, the Transportation Efficiency Act of the 21st Century extended the ethanol tax credit through 2007 but stipulated gradual reductions from $0.54 to $0.51 per gallon by 2005.[14] The American Job Creation Act of 2004 extended the tax credit out to 2010 but changed the structure from an excise tax exemption to a blender's tax credit. More commonly referred to as the "blender's

[14] The tax credit was reduced to $0.53 per gallon in 2001 and $0.52 per gallon in 2003.

credit," the Volumetric Ethanol Excise Tax Credit (VEETC) maintained the subsidy value at $0.51 per gallon. The 2008 Farm Bill, which introduced new incentives for cellulosic biofuel production (i.e., producer tax credit and BCAP), lowered incentives for conventional biofuel by reducing the VEETC to $0.45 per gallon.

The year 2011 was historic for the ethanol industry. After three decades of continued support, the Senate voted to repeal the ethanol tax credit (VEETC) on June 16. Congress let the tax credit and corresponding tariff expire December 31. In total, tax credit programs for conventional ethanol provided roughly $20 billion of support to the ethanol industry over the 30-year period.

Appendix A.1 provides a summary timeline of the U.S. federal ethanol policies. Although not addressed in this chapter, state-level policies also had important implications on industry growth. Detailed discussions of state-level ethanol policies are provided by Duffield, Xiarchos, & Halbrook (2008), FAPRI (2008), Kesan & Ohyama (2011).

2.3 Biofuel policy drivers

As evidenced in the previous section, government support for biofuels has a long history. What has motivated such strong government intervention in the biofuel industry and have these motivations changed over time? The primary policy drivers in the early stage of industry development were energy independence and agricultural support (Tyner W. , 2011). After the CAAA of 1990, air quality benefits of biofuel relative to conventional fuels became increasingly relevant. Tyner (2011) and Solomon, Barnes, & Halvorsen (2007) argue the primary objectives of current support are energy security and GHG emissions reductions. This argument is consistent with recent statements from the U.S. Department of Energy (DOE): "growing concerns over national energy security and climate change have renewed the urgency for developing sustainable biofuels, bioproducts, and biopower" (U.S. DOE, 2011a, p. 1).

Although priorities have shifted over time, the three most commonly mentioned motivations for biofuel support include:

1) energy independence from or reduced dependence on imported petroleum

2) rural economic development opportunities provided by biofuel expansion

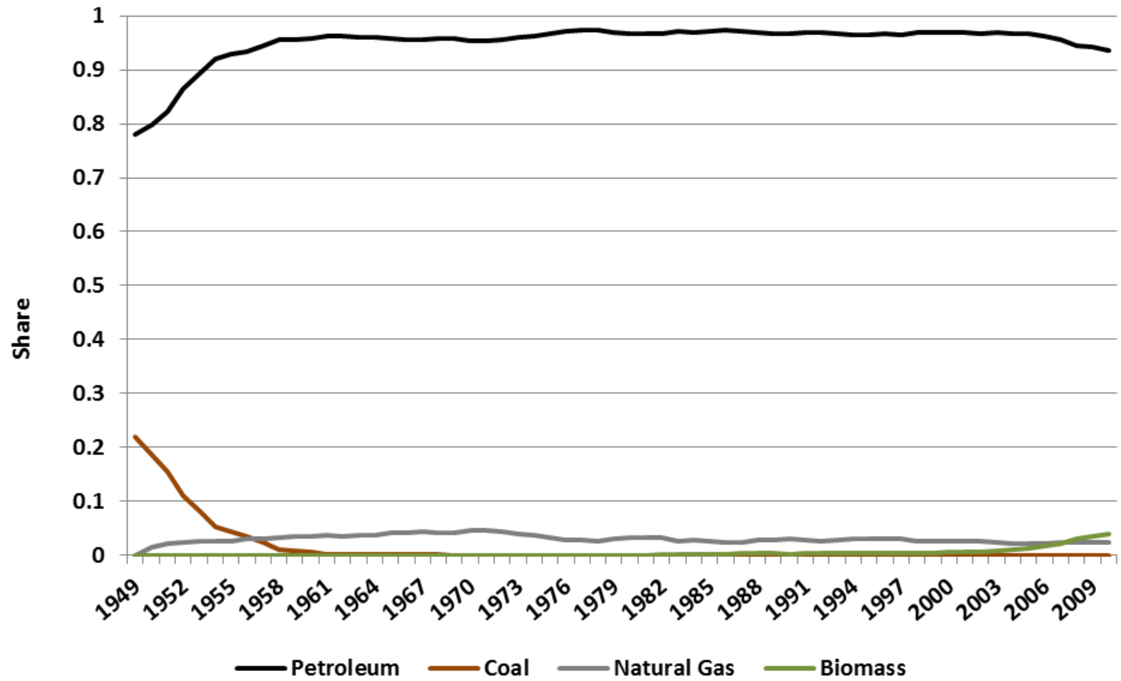
3) potential environmental benefits associated with substituting biofuel for fossil fuels

Each of these motivations is considered in more detail in the following subsections.

2.3.1 Energy independence and security

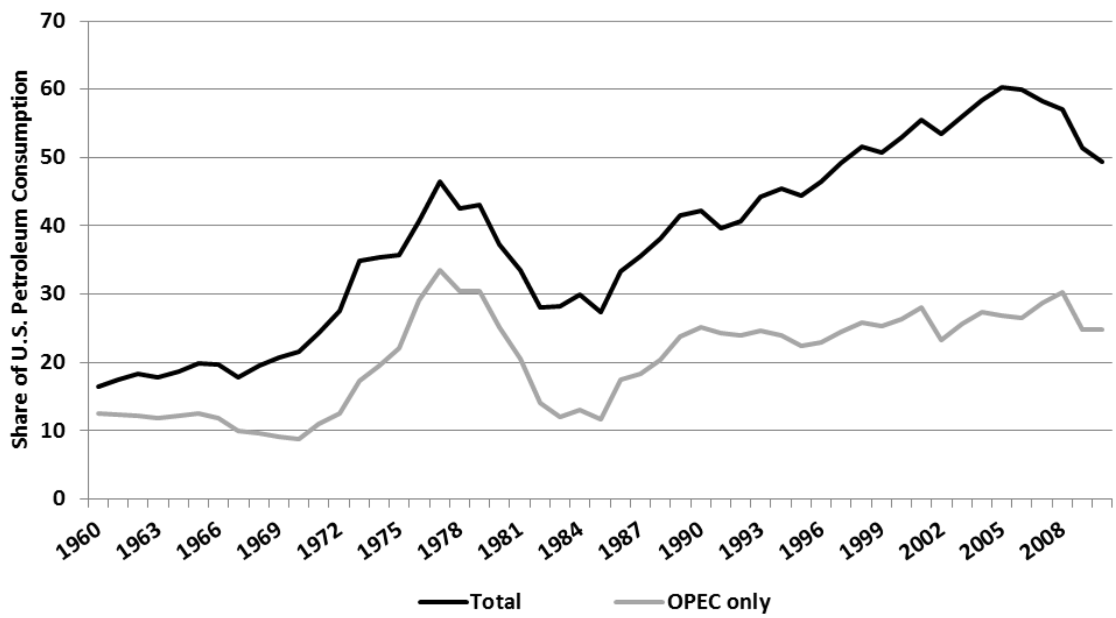
The U.S. transportation sector is heavily reliant on petroleum-based fuels (see Figure 2.6). Between 1960 and 2010, petroleum provided approximately 96% of the energy consumed within the transportation sector. Over this same time frame, decreases in domestic petroleum production coupled with increased transportation demand led to greater dependence on foreign oil. Figure 2.7 illustrates the increase in net petroleum imports as a share of total petroleum consumption between 1960 and 2010. In 1960, net imports constituted 16.5% of U.S. petroleum consumption. This share has experienced gradual increase over time, with the exception of a spike in the mid-to-late 1970s. After peaking at 60% in 2005, the share of imports has gradually fallen to around 50% in 2010. This fall in the share of petroleum imports coincides with the period of rapid expansion in the use of biomass (including corn) as a transportation fuel source (see Figure 2.6). Consequently, the ability of biofuels to reduce reliance on imported energy, especially from unstable and unfriendly national governments, has been suggested as a way to improve national security, economic health, and future global competitiveness (U.S. DOE, 2011a).

Figure 2.6 – Fuel source as a percent of energy consumption in the U.S. transportation sector (1949-2010)



Source: Annual Energy Review (U.S. EIA, 2011). Table 2.1e – Transportation Sector Energy Consumption Estimates (1949-2010).

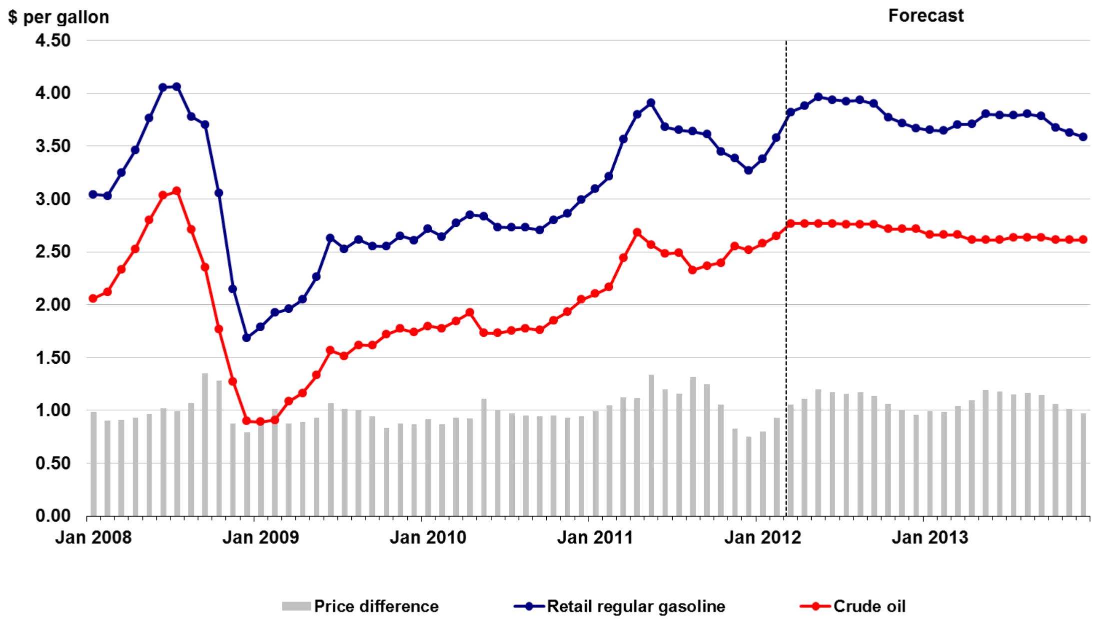
Figure 2.7 – U.S. net petroleum imports as share of total petroleum consumption (1960 – 2010)



Source: Annual Energy Review (U.S. EIA, 2011). Table 5.7- Petroleum Net Imports by Country of Origin, 1960-2010.

The dependence of the transportation sector on petroleum-based fuels also has consequences for energy prices. Any price volatility in the petroleum market will be experienced in the transportation fuel market and, although to a lesser extent, markets for other energy sources. Figure 2.8 shows the path of U.S. crude oil and gasoline prices between January 2008 and January 2012. Projected prices through 2013 are also provided. The price of gasoline traces along the price of crude oil, maintaining a price difference around $1.00 per gallon. The prevalent short-run fluctuations in oil price have translated into prevalent short-run fluctuations in transportation fuel price.

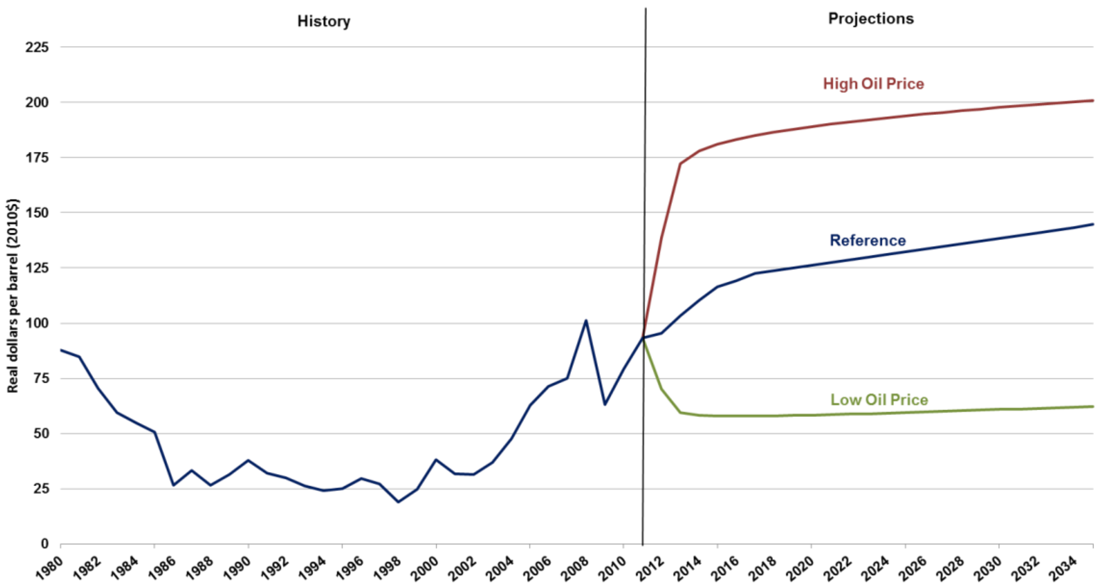
Figure 2.8 – U.S. gasoline and crude oil prices (2008 – 2013)



Note: Crude oil price is average refiner acquisition cost. Retail prices include State and Federal taxes.
Source: U.S. EIA (2012b). Short-Term Energy Outlook, March 2012

Volatility in the price of oil is not a recent or short-run phenomenon. Figure 2.9 shows the average annual world oil price between 1980 and 2011 along with three oil price forecasts out to 2030. The volatility of the real oil price has been rather persistent over the long-run. This uncertainty underlies the large difference between the high and low oil price projections. For example, the 2035 high oil price forecast is $201 per barrel while the low oil price forecast is $62 per barrel. Both the reference and high oil price scenarios anticipate a significant rise in the price of oil between 2011 and 2035 – a 55% increase in the reference scenario and 115% increase in the high cost scenario.

Figure 2.9 – Average annual world real oil price with three price projections, 1980 – 2035



Source: U.S. EIA (2012a). AEO2012 Early Release Overview – Figure 5.

Rising and more volatile energy prices, including the oil price shock of 2008, have encouraged arguments from biofuel proponents. In particular, that biofuels would provide a substitute for petroleum-based transportation fuels, thereby increasing competition in the transportation fuel market. Increased competition has the potential to reduce long-run energy prices as well as alleviate severity of short-run price fluctuations.

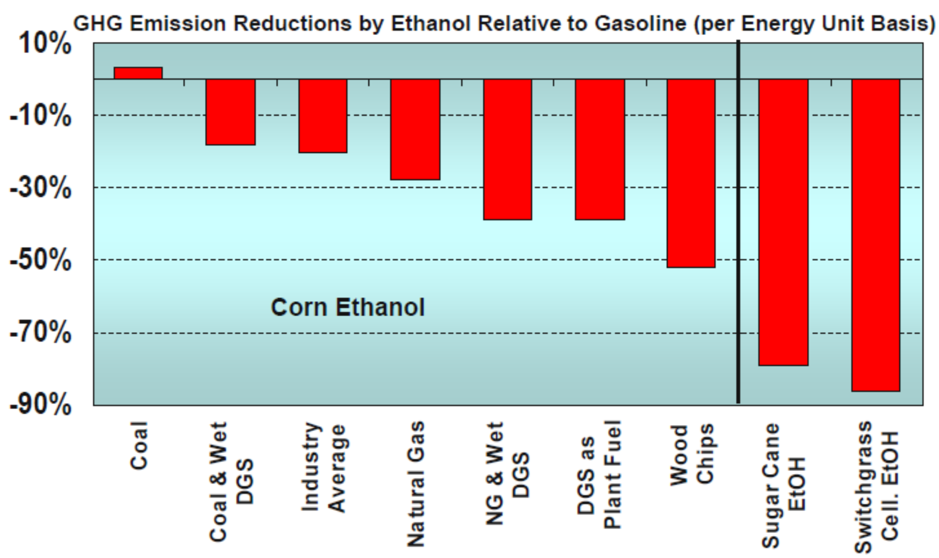
2.3.2 Agricultural and rural economy support

Ethanol production benefits the agricultural sector through increased feedstock demand and higher commodity prices (Tyner, 2011; Duffield, Xiarchos, & Halbrook, 2008). Rural economies can further benefit from increased land values and job opportunities. The generation of off-farm work may help offset recent increases in rural migration and unemployment (Lambert, Wilcox, English, & Stewart, 2008). Yet, Swenson (2006) finds that previously high, positive rural impacts attributed to corn-ethanol production likely overstated the actual impacts through generous multiplier effect assumptions or failure to account for shifting labor and resources. Further, Miranowski et al. (2008) suggest economic gains for rural areas may be limited due to competition for land and biomass between livestock feed, food, and biofuel feedstock.

2.3.3 Climate change and environmental concerns

The U.S. transportation sector is responsible for approximately one-third of U.S. carbon dioxide (CO_2) emissions (U.S. DOE, 2011a). Biofuels not only provide a renewable energy source but have potential to lower transportation-related GHG-emissions.[15] Figure 2.10 shows estimates of the reduction in GHG emissions relative to gasoline. The impact of corn-grain ethanol relative to gasoline ranges from a 3% increase in emissions with a coal-operated refinery to a 52% reduction if wood chips are the process fuel. Cellulosic ethanol is expected to provided higher GHG emissions reductions. For example, switchgrass-based ethanol is estimated to reduce GHG emissions by 86% relative to gasoline (Wang, Wu, & Huo, 2007).

Figure 2.10 – Ethanol GHG emissions reductions



Source: Wang (2007). Slide 19. GREET model estimates.

[15] Disagreement exists regarding the GHG-emissions impact of biofuels. Searchinger et al. (2008) argued indirect land use change from large scale biofuel production would create a carbon debt that would take up to 167 years to offset. Matthews & Tan (2009, p. 305) evaluate the validity of the assumptions used by Searchinger et al. and suggest "land use change effects are too diffuse and subject to too many arbitrary assumptions to be useful for rule-making."

2.4 First-generation biofuels and transition to second-generation biofuels

First-generation biofuels refer to biofuels derived from sugar-, oil-, or starch-based sources. The majority of first-generation biofuel produced in the United States is corn-based ethanol, also referred to as conventional biofuel. Corn ethanol can be produced using a wet- or dry-mill process.[16] A wet-mill refinery has the flexibility to produce a variety of final products beyond ethanol including starch, corn syrup, Splenda, etc. The flexibility to shift between final products allows the refinery to be more responsive to market conditions (Dale & Tyner, 2006). A dry-mill refinery does not have the final product flexibility of a wet-mill, but benefits from lower construction and operating costs and greater efficiency at turning corn into ethanol (Dale & Tyner, 2006; Feng, Rubin, & Babcock, 2008).

Wet-mill refineries dominated U.S. ethanol production prior to 2000. A shift towards dry-mill processing began in the early 2000s as the price of ethanol rose with increased biofuel demand. In 2010, 87% of corn ethanol production used a dry-mill process (Feng, Rubin, & Babcock, 2008). Dry-mill production has a valuable co-product called distillers grains with solubles. Distillers grain contains the fiber, protein, vegetable oil, and minerals left after the starch components have been removed to produce ethanol.[17] Approximately one-third of the original corn weight is returned in distillers grain (U.S. DOE, 2011b).

As of January 2012, the total U.S. capacity for corn ethanol was 14.6 billion gallons (RFA, 2012b; RFA, 2012a). Therefore, current capacity is available to meet or exceed the 2012 RFS2 conventional biofuel mandate of 13.2 billion gallons. An additional 130 million gallons of capacity from current construction and expansion projects will push the industry above 15 billion gallons – the level at which the conventional mandate plateaus in 2015. Approximately one-third of the U.S. annual corn production is expected to be used for ethanol production through 2020 (U.S. DOE, 2011b).

[16] Detailed descriptions of corn-ethanol production processes are available in Brown (2003), Bothast & Schlicher (2005), and Kwaitkowski et al. (2006).

[17] Livestock can be fed distillers grain in either a wet or dried form (U.S. DOE, 2011b). Although dried distillers grain with solubles (DDGS) incurs an additional drying cost, it can be stored for longer periods of time and is more convenient and economical to transport than wet distillers grain with solubles (WDGS).

Rapid growth in the corn ethanol industry was not without its critics. Rosillo-Calle & Tschirley (2010, p. 8) consolidate the criticisms of first-generation biofuel into three major dilemmas:

"(1) whether biofuel production and use lead to – or imply – a choice between food and fuel;

(2) whether biofuels have positive or negative effects for climate change and the broader environment; and

(3) whether biofuels contribute to social-economic development, wealth generation and distribution."

The 'food-versus-fuel' debate is the most publicized criticism of first-generation biofuels. The debate centers on the use of food crops as biofuel feedstocks. This is not a new debate. The Brazilian alcohol program, implemented in 1975, faced similar criticism over sugar-based alcohol (Rosillo-Calle & Hall, 1987). The debate over corn-based ethanol escalated in 2007 and 2008 as agricultural commodity prices spiked, leading to what some referred to as a global food crisis. Although several factors contributed to the rise in commodity prices, U.S. ethanol policies were attacked for incentivizing the use of large quantities of food crops for fuel.[18] Rising food prices led some countries, such as China, to stop or reduce programs that support biofuel from food crops (Sorda, Banse, & Kemfert, 2010).

The food-versus-fuel debate, coupled with other concerns, raised question to the ability of first-generation biofuels to provide a long-run alternative for fossil fuels (Lardon, Helias, Sialve, Steyer, & Bernard, 2009). Attention and interest began to turn towards 'second-generation' or biomass-based biofuels. The Energy Security Act of 1980 defines biomass as: "any organic matter which is available on a renewable basis, including agricultural wastes and residues, wood and wood wastes and residues, animal wastes, municipal wastes, and aquatic plants" (U.S. DOE, 2009).[19] The

[18] Babcock & Fabiosa (2011) decomposed the cause of the corn price increase between 2006 and 2009. Corn ethanol expansion from both market forces and subsidies was found to account for 36% of the increase in corn prices. The remaining 64% was attributed to other market forces.

[19] Riedy & Stone (2010) provide a comparison of biomass definitions in legislation. Recent statutes and tax codes contain 16 different biomass definitions.

most commonly mentioned second-generation biofuel is cellulosic biofuel. Cellulosic biofuel is biofuel derived from the structural material of plants such as wood, grasses, and crop residues. Cellulosic biofuels avoid, or at least assuage, some of the issues faced by first generation biofuels. Relative to first-generation biofuels, second-generation biofuels are expected to be more water-efficient, require less arable land, and provide higher net energy balances and GHG emissions benefits (Schenk, et al., 2008; Wang, Wu, & Huo, 2007). Samuel Bodman, former U.S. Energy Department Secretary, acknowledged the importance of the transition to second-generation biofuel in a 2008 speech (Bodman, 2008):

> *"So, as we pursue diversity in our overall energy mix we must also pursue diversity in our biofuels. This means moving away gradually from ethanol produced from food stocks like corn. Let me be clear: I am not minimizing the importance of ethanol made from corn - it is critical to our energy security and America's farmers make an important contribution to our energy security. But what I am saying is that we need to develop and deploy the next generation of ethanol - ethanol and other products made from biomass products that are outside the food chain. In my view, this means cellulosic fuels made from agricultural waste products and crops like switchgrass, which can be grown and regenerated on less desirable lands."*

The next section provides an overview of potential biomass feedstocks for second-generation biofuel along with the economic and environmental challenges of commercial scale production.

2.5 Alternative biomass sources

Biomass is separated into 2 major categories: wastes and dedicated energy crops. A material is classified as waste if it has no value or is a nuisance to the local environment. Alternatively, plants grown intentionally for production of bio-based products are called dedicated energy crops (Brown, 2003). Table 2.2 breaks down the classification of biomass resources and provides examples for each type.[20]

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[20] The process of converting biorenewable resources into ethanol will vary based on the type of feedstock. Appendix A.2 provides descriptions for some of the possible methods for biomass-to-ethanol conversion. The appendix is not a comprehensive list of possible methods, but describes the approaches and limitations of the most widely accepted processes. Refer to Brown (2003), Kaylen et al. (2000), or Hamelinck et al. (2005) for a more detailed overview.

Table 2.2 – Biomass resource classification

Biomass resource	Examples
Wastes	
Agricultural residue	corn stover, rice hulls, wheat straw, bagasse, grapevine prunings, almond shells
Yard waste	grass clippings, leaves, tree trimmings
Food processing waste	cereal processing, brewery waste
Manure	
Municipal solid waste (MSW)	garbage
Dedicated Energy Crops	
*Oil-based^*	soybeans, nuts, grains
*Sugar-based^*	sugar beets, sorghum, sugar cane
*Starch-based^*	corn, cereal crops
Lignocellulosic	
Herbaceous energy crops (HEC)	
Thick-stemmed grasses	sugarcane, sorghum
Thin-stemmed grasses Cool-season Warm-season	 fescue, reed canary grass switchgrass, big bluestem
Short-rotation woody crops (SRWC)	
Hardwoods	willow, oak, poplar
Softwoods	pine, spruce, cedar

Source: Adapted from Brown (2003)
^Considered first-generation biofuel sources

Waste material

Categories of waste material include agricultural residue, yard waste, food processing waste, manure, and municipal solid waste. Agricultural residues are the portion of the plant not collected during harvest. Examples of agricultural residue include corn stover, rice hulls, wheat straw, bagasse, grapevine prunings, and almond shells. Yard waste consists of grass clippings, leaves, and tree trimmings. A major disadvantage of yard waste is seasonal variation. Supply and consistency will vary depending on the season, typically dry during the fall and wet during the spring. Food processing waste consists of waste matter from a variety of industries. Since production processes within these industries do not change frequently, consistency in composition and supply is an advantage. Yet, food processing wastes tend to contain materials and chemicals that complicate conversion. Municipal solid waste (MSW) is everything thrown in the garbage, but only a fraction of this waste is a viable energy source. MSW is easily accessible but inconsistent composition and supply make it an unreliable feedstock source (Brown, 2003).

One potential advantage of waste materials is cost. For most wastes, the major costs include collection, transportation, and storage. Some waste material can even be obtained at negative or zero costs. For example, people pay to dispose of landfill waste. Wheat producers also occasionally pay to burn wheat straw in order to avoid grain planting problems during the following crop season. These cost advantages of waste feedstocks make these some of the most attractive resources for the biofuel industry (Brown, 2003).

A potential exception to this low-cost argument is crop residues such as corn stover. The economic and environmental impacts from residue removal have caused debate. Uncollected residue has value to the soil through protection against rain, wind, and radiation, thereby limiting erosion. Erosion results in the loss of organic-matter-rich topsoil, which diminishes soil quality and subsequent crop yields (Wilhlem, Johnson, Hatfield, Voorhees, & Linden, 2004).[21] Unharvested crop residues also replenish soil organic carbon, which is reduced as a result of crop production activities. Recent evidence suggests the amount of residue needed to maintain soil organic carbon is a greater constraint than residue needed to control water and wind erosion (Wilhelm, Johnson, Karlen, & Lightle, 2007).

Demand for crop residues as biofuel feedstocks creates a trade-off for potential biomass suppliers. If harvested, residue provides an immediate economic return. If left unharvested, residue may provide soil and water benefits for future crop production (Karlen D. , 2010). Landowners must consider the long-run impacts of residue removal. Sustainable residue removal will vary based on the crop, soil type, and soil properties. Standard production practices for residue management currently do not exist but a model such as the Revised Universal Soil Loss Equation (RUSLE2) is recommended for guidance (Andrews & Aschmann, 2006). General guidelines may develop in the future as the industry develops. Additional discussion on the environmental and productivity impacts

[21] Erosion also impairs rivers and lakes as fertilizer, nutrients, and other agricultural residues run off into waterways (Ribaudo & Johansson, 2006).

of residue removal are provided in Andrews (2006), Blanco-Canqui (2010), Blanco-Canqui & Lal (2007), Karlen (2010), and the updated Billion-Ton Study (U.S. DOE, 2011b).

Residue removal concerns are not universal. For some areas, partial removal of residue may not impact future productivity and may even provide productivity benefits for areas with higher residue production. In these cases, crop residues are an appealing biomass feedstock as an established crop with lower costs and relatively concentrated availability (U.S. DOE, 2011b).

Dedicated Energy Crops

Dedicated energy crops are crops planted specifically for energy use and not human or animal consumption. There are four main energy components in dedicated energy crops: oils, sugars, starches, and lignocellulose. Although oil-, sugar-, or starch-based crops can be grown as dedicated energy crops, they are easily metabolized and primarily grown for human or animal consumption. As a result, oil-, sugar-, and starch-based feedstocks are considered first-generation biofuel sources.

Lignocellulosic materials, such as grasses and woody biomass, are difficult to break down and typically indigestible by the human body. Biofuel from lignocellulosic material is considered a second-generation biofuel, referred to as cellulosic biofuel. Lignocellulosic crops are an attractive biofuel source for their higher energy values. Development of a cellulosic biofuel industry could be highly valuable since agricultural residues also contain lignocellulosic material (e.g. stems, leaves, roots). Not only would the biofuel industry be able to take advantage of dedicated lignocellulosic crops, but could also utilize agricultural residues. The following subsections describe two categories of lignocellulosic crops: herbaceous energy crops (HEC) and short-rotation woody crops (SRWC) (Brown, 2003).

Herbaceous Energy Crops (HEC)

The main characteristic separating HEC from SRWC is a lack of woody tissue. HEC can be annual or perennial, but the above-ground portion of the plant only survives one growing season. The plants are harvested at least once a year and, depending on plant characteristics and locations, may be harvested multiple times. Harvest yields tend to be higher in tropical and subtropical regions.

The most notable herbaceous energy crops, due to higher lignocellulose content, are grasses. Grasses are classified as either thick-stemmed or thin-stemmed. Thick-stemmed grasses originate from the tropics and can be annual or perennial. Examples include sugarcane (perennial) and sorghum (annual). One disadvantage of thick-stemmed grasses is the labor-intensive, and therefore costly, harvest process. Thin-stemmed grasses can also be perennial or annual and contain both cool-season and warm-season grasses. Warm-season grasses tend to be more nutrient efficient and drought-resistant. Two common thin-stemmed grasses are fescue (cool-season) and switchgrass (warm-season). Thin-stemmed grasses can be harvested with conventional hay equipment, a major advantage over thick-stemmed grasses. Thin-stemmed grasses also do not exhibit the degree of lodging observed in thick-stemmed grasses, or plants falling on each other as they increase in height, offering more flexibility in harvest timing (Brown, 2003).

Switchgrass (*panicum virgatum*), a warm-season perennial grass native to North America, was identified by the U.S. Department of energy (DOE) as the model herbaceous energy crop for biofuel feedstock (Wright & Turhollow, 2010).[22] Minimal fertilization requirements and a deep root system, which provides drought and high temperature tolerance, make switchgrass an attractive crop for marginal land (Crooks, 2006; U.S. DOE, 2011b). The long root system also stores carbon deep in the soil rather than at the surface level limiting carbon escape during recovery (Comis, 2006).

Compared to major U.S. farm crops, switchgrass has several advantages. Even if harvested annually, switchgrass provides improved wildlife habitat and hunting opportunities (U.S. DOE, 2011b). As a perennial crop, little management is needed after establishment. Avoiding annual tillage reduces the potential for soil, water, and fertilization loss (Comis, 2006; Mitchell, Vogel, Schmer, &

[22] Wright (July 2007) and Mitchell, Vogel, Schmer, & Pennington (2010) provide historical background surrounding the selection of switchgrass as the model herbaceous energy crop.

Pennington, 2010). Switchgrass also yields about four times the cellulosic material and seven tons more soil carbon per acre than corn (Comis, 2006; Crooks, 2006). With higher cellulosic material per acre and less energy-intensive production, switchgrass provides three times the net energy gain compared to corn when converted into ethanol (Crooks, 2006).

Switchgrass is not without limitations. Yields are lower during the first three years as the plant germinates and increases in density. Growth can be limited by weed competition, seed dormancy, and poor seedling vigor. Even though switchgrass requires limited fertilization, weed control is necessary for plant development (ISU Agronomy, 2007). For switchgrass to provide enough feedstock to sustain a commercial-scale biorefinery, a large amount of land will need to shift from current activities into switchgrass production. Large shifts in land use may alter wildlife habitat and other environmental benefits associated with current ecosystems. Although research and farming of switchgrass in the United States goes back more than 70 years (Mitchell, Vogel, Schmer, & Pennington, 2010), the harvest, storage, and transport of enough switchgrass to operate a commercial scale biorefinery is uncharted territory. Research on commercial scale switchgrass production is still on the early part of the learning curve and the potential long-run environmental impacts are unknown.

Another perennial grass which has gained recent interest as a potential biofuel feedstock is *Miscanthus*. Considerable study of *Miscanthus* has been conducted throughout Europe including direct combustion for local power generation (Heaton, Clifton-Brown, Voight, Jones, & Long, 2004a). As a non-native grass to North America, *Miscanthus* research in the United States has been limited, but recent trials in Illinois provided evidence of *Miscanthus'* potential as a biofuel feedstock in the United States. *Miscanthus* provided more than four times the quantity of biomass in a side-by-side trial with switchgrass. Compared to corn grain, *Miscanthus* was estimated to provide 260% more ethanol per hectare (Heaton, Dohleman, & Long, 2008). Challenges of commercial scale *Miscanthus* production in the U.S. are similar to those for switchgrass. In addition, *Miscanthus* is a non-native grass which raises concerns about invasiveness (U.S. DOE, 2011b).

Short-Rotation Woody Crops (SRWC)

Short-rotation woody crops (SRWC) are defined as woody biomass that is fast growing and suitable for use in dedicated feedstock supply systems (Brown, 2003). Valuable characteristics include rapid juvenile growth, wide site adaptability, and pest and disease resistance. Harvest rotations range from 3-12 years. SRWC can be classified as hardwoods or softwoods. Hardwoods are flowering plants (angiosperms) including willow, oak, and poplar. Hardwoods have many advantages including higher density, ease of delignification, and carbohydrate accessibility. Softwoods include most evergreens (gymnosperms) such as pine, spruce, and cedar. Softwoods are advantageous due to their fast growth, and have value as construction lumber and pulpwood, which makes softwood waste readily available. Yet, the carbohydrates are not as accessible in softwoods as in hardwoods. Therefore, development in SRWC has focused mainly on hardwoods for feedstock supply systems. In the United States, hybrid poplar and eucalyptus have the most potential as biofuel sources. Other hardwood feedstock sources include: alders, mesquite, Chinese tallow, willows, silver maple, sweetgum, sycamore, and black locust (Brown, 2003). SRWC offer similar advantages as perennial grasses in terms of improved soil productivity and wildlife habitat.

Although not classified within the SRWC, forest residues are another source of woody biomass. Forest thinning can provide feedstock for biofuel while improving forest health if sufficient structure is left for cover, erosion control, and habitat (Graham, McCaffrey, & Jain, 2004). Similar to agricultural residues, some forest residue should be left for the benefit of the forest ecosystem – for example, residues provide habitat for wildlife and other organisms, nurse logs for seed germination, water management, etc. (Harmon, et al., 2004; U.S. DOE, 2011b). Disadvantages of forest residues stem from accessibility and recovery issues. Many forest areas lack sufficient roads or open areas for the large equipment needed to remove and transport timber material (Perlack, Wright, Turhollow, Graham, Stokes, & Erback, April 2005).

Biomass potential

With several alternative feedstock sources, biomass has the potential to significantly contribute to the U.S. energy sector. In 2005, a U.S. DOE project out of Oak Ridge National Laboratory evaluated the feasibility of a U.S. billion-ton annual supply of biomass (Perlack, Wright, Turhollow, Graham, Stokes, & Erback, 2005). Commonly referred to as the “Billion-Ton Study,” the report concluded that 1.3 billion dry tons of biomass could be supplied annually towards biofuels with changes in land use and agricultural and forestry practices. This quantity of biomass would offset approximately 30% of U.S. petroleum consumption. A 2011 update to the Billion-Ton Study attempted to address some of the shortcomings of the original report. Although contributions from crop residue and forests were lower in the updated report, increased energy crop estimates offset these, resulting in a relatively unchanged total biomass supply.

Another study from the Bio-based Energy Analysis Group at the University of Tennessee proposed and evaluated the possibility of achieving 25 percent of U.S. energy consumption from the agricultural and forestry sectors by 2025, denoted as the 25x`25 goal (English, et al., 2006). While feasible, major increases in dedicated biomass production would be needed to meet this goal.

Second-generation biofuels do not use major food crops such as corn for feedstock, but this does not imply development of the second-generation biofuel industry will not impact commodity markets. First, demand for dedicated biomass crops will increase competition for land. Second, some types of biomass, such as crop residues, are currently used for livestock feed or bedding. A significant increase in demand for these resources as biofuel feedstocks may increase costs of commodity production.

2.6 State of industry and market uncertainty

Second-generation biofuel production in the United States is currently limited to small or demonstration scale facilities; a commercial scale second-generation biorefinery does not exist. Table

2.3 details the biomass-to-ethanol plants currently operating including location, feedstock, and capacity. Given the cost advantages of utilizing food and beverage waste for biofuel, several waste-to-ethanol biorefineries are operating, but the largest facility is 5.4 mgy.

Table 2.3 – Biomass-to-ethanol plants operating and under construction

Company	**Location**	**Feedstock**	**Capacity** (mgy)
Constructed			
BP Biofuels North America	Jennings, LA	Sugar cane bagasse	1.4
Fiberight, LLC^	Blairstown, IA	MSW	5
Golden Cheese Company of California^	Corona, CA	Cheese whey	5
KL Process Design Group	Upton, WY	Wood waste	1.5
Land O'Lakes	Melrose, MN	Cheese whey	1.5
Merrick and Company	Aurora, CO	Waste beer	3
Parallel Products	Louisville, KY	Beverage waste	5.4
POET	Scotland, SD	Corn stover	0.20
Summit Natural Energy	Cornelius, OR	Waste sugars/starches	1
UTBI	Vonore, TN	Corn stover and switchgrass	0.25
Wind Gap Farms	Baconton, GA	Brewery Waste	0.4
Under construction			
Abengoa Bioenergy Corp.	Hugoton, KS	Crop residue & energy crops	25
Dubay Biofuels Greenwood	Greenwood, WI	Cheese whey	20
DDCE	Nevada, IA	Corn stover	40
POET	Emmetsburg, IA	Corn stover	25

Source: http://www.ethanolrfa.org/bio-refinery-locations/
^ Constructed but currently not operating

A 25 mgy cellulosic ethanol plant proposed by POET for Emmetsburg, Iowa is expected to be the first commercial scale cellulosic biorefinery in the United States. The technology for the Emmetsburg plant will be based on POET's pilot scale plant in Scotland, South Dakota. The biorefinery was originally scheduled to be completed and operational by 2011 but faced several setbacks including a delay in the government loan. The facility now is expected to be operational in 2013. DuPont Danisco Cellulosic Ethanol (DDCE) announced in June 2011 plans to build a 40 mgy plant in Nevada, Iowa. The proposed biorefinery will use technology from UTBI's pilot plant in

Vonore, Tennessee.[23] Both the POET and DDCE biorefineries intend to use corn residue for feedstock.

Despite policy incentives for second generation biofuel production and the existence of several biomass-to-biofuel conversion methods (Swanson, Platon, Satrio, & Brown, 2010; Kazi, et al., 2010a; Wright, Daugaard, Satrio, & Brown, 2010), investment has been limited by current costs of production and uncertainty in future policies and market conditions. Rosburg & Miranowski (2011) estimate ethanol producers would lose \$0.82 - \$1.65 per gallon of ethanol (\$1.23 – \$2.47 per gallon gasoline equivalent, 2007\$) given current production costs, a long-run oil price of \$100 per barrel, and no policy incentives. Alternatively, the long-run price of oil would need to be around \$135 - \$170 per barrel for cellulosic ethanol production to break even without significant government intervention. The U.S. Energy Information Agency (EIA) forecasts oil prices of \$129 per barrel in 2022 and \$145 per barrel in 2035 in their reference scenario (2010\$) (see Figure 2.9).

Feedstock procurement is one area in which costs are expected to decrease. Ongoing research is attempting to identify ways to reduce costs and increase efficiency of commercial scale biomass harvest, storage, and transport. Yet, even with a more efficient biomass supply system, the biorefinery is still dependent on a non-commercialized feedstock with variable annual supply. Given the novelty of commercial scale biomass production, potential investors may be hesitant to invest without a better understanding of the potential variation in feedstock supply and/or strategies to lay off risk associated with feedstock variability. In addition to variation in quantity, the variation in biomass quality is a cause for concern. The quality of final product is directly related to the composition of delivered biomass. Production costs rise as additional processes are needed to treat heterogeneous biomass with undesired contents (Wright, Daugaard, Satrio, & Brown, 2010).

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[23] The University of Tennessee Biofuel Initiative (UTBI) is a joint venture between the University of Tennessee, University of Tennessee Research Foundation (UTRF), UT Institute of Agriculture (UTIA), Genera Energy LLC, and DuPont Danisco Cellulosic Ethanol, LLC (DDCE).

Biorefinery investment decisions also depend on expectations about future market demand and government policies (Lin & Yi, 2011). If continued and enforced, government policy programs reduce uncertainty for potential biomass suppliers and biorefinery investors. The cellulosic biofuel producer tax credit is still in effect but is up for renewal on December 31, 2012. Recent resistance to the conventional ethanol tax credit, as well as the biodiesel tax credit, may be an indication of the political environment the cellulosic industry will face in December.

More crucial is the uncertainty in the RFS2 cellulosic biofuel mandates. Discussed in Box 2.1, the EPA Administrator is authorized to waive part or all of the cellulosic sub-mandate; the Administrator has used this right every year since the first cellulosic mandate in 2010. If the mandates were enforced, market-based policies such as the biofuel producer tax credit would not be needed to incentivize biofuel production (Babcock B. , 2010; GAO, 2011; NRC, 2011).[24] Further, guaranteed market demand for biomass would reduce risk associated with perennial crop production while cellulosic biofuel investors would be ensured future demand for their product (Mallory, 2011). However, the EPA's ability to waive part or all of the cellulosic sub-mandate fosters uncertainty in the minds of potential biomass suppliers and biorefinery investors. In short, a policy cannot reduce uncertainty unless it is certain itself.[25,26]

The possibility of future cellulosic mandate waivers also creates uncertainty in markets for agricultural commodities and other biofuels. Thompson & Meyer (2011) detail three different ways the EPA could implement a cellulosic mandate waiver and the potential impact on other biofuel markets:

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[24] With enforced mandates, tax credits or subsidies would have no impact on the level of biofuel production unless the price of oil increased enough such that higher market demand for biofuel together with subsidy payments pushed ethanol production above the mandated level (Babcock B. , 2010).

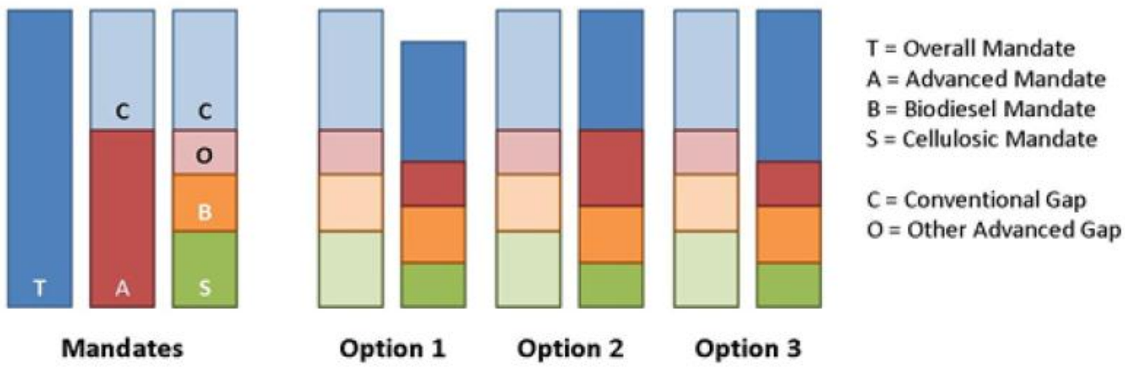
[25] Rupert Edwards, Head of Research and Market Analysis at Climate Change Capital, used a similar phrase in reference to the UK Government's carbon policy proposals: "a policy meant to reduce uncertainty must itself be certain."

[26] Additional discussions on the conditions for and limitations of investment in commercial scale biofuels are available in Babcock, Marette, & Tréguer (2011) and Kenkel & Holcomb (2009).

1. Reduce the cellulosic sub-mandate, advanced biofuel mandate, and total biofuel mandate by the same quantity.
2. Reduce the cellulosic sub-mandate but maintain the advanced and total biofuel mandates.
3. Reduce the cellulosic sub-mandate and advanced biofuel mandate by the same quantity but maintain the total biofuel mandate.

Option 1 is a universal reduction and will not impact other biofuel categories. If the EPA Administrator uses Option 2, other advanced biofuels such as biodiesel will need to compensate for the waived cellulosic biofuel quantity. Option 3 shifts the waived cellulosic biofuel quantity to the conventional biofuel mandate or to corn-based ethanol. Figure 2.11 illustrates these three options.

Figure 2.11 – RFS2 mandates and three options for waiving the cellulosic mandate



Source: Meyer and Thompson (2011). *Figure 2.*

The flexibility of the EPA Administrator to choose between Options 1, 2, or 3 introduces new uncertainty for future biodiesel, corn ethanol, and agricultural commodity markets. Depending on which option the administrator chooses to implement the waiver, market demand for U.S. biodiesel and corn ethanol could vary by several billion gallons per year (Thompson & Meyer, 2011).

With the tax credit up for renewal and continued reductions in the RFS2 cellulosic mandate, some have proposed modifications to current biofuel policies (GAO, 2011; Irwin, Good, & Mallory, 2011; Mallory, 2011; Tyner, 2011; Tyner, Brechbill, & Perkis, 2010; Tyner, Taheripour, & Perkis, 2010). In terms of tax credits, one suggested modification is to make tax credits variable with ties to either the price of oil or the blending margin (Tyner, Taheripour, & Perkis, 2010; Irwin, Good, & Mallory, 2011; Tyner, Brechbill, & Perkis, 2010; NRC, 2011). While a tax credit of this form may reduce government spending by removing support when market conditions make biofuels competitive, it would not directly reflect policy objectives such as GHG emissions reductions (NRC, 2011).

To incentivize biorefinery investment, Mallory (2011) proposes an investment tax credit or a one-time payment to lower capital investment costs. This program would reduce the pay-back period on investment, thereby lowering investment risk.

Given GHG emissions benefits is a common policy objective for biofuel support, Tyner (2011) suggests making any subsidy payments at least partially dependent on biofuel-specific GHG reductions as determined by an independent entity. One option is to divide subsidy payments into two parts – the first part as a fixed payment per gallon biofuel and the second part variable based on GHG emissions reductions. This type of support mechanism would incentivize biofuel processors to reduce GHG emissions (NRC, 2011).

2.7 Other challenges of cellulosic biofuel expansion

Growth of the cellulosic biofuel industry has and will continue to face challenges beyond investor uncertainty. A few key challenges to industry development are discussed in the following. A more detailed discussion on the challenges of biofuel expansion is available elsewhere (NRC, 2011).

A significant amount of land will need to be allocated into dedicated biomass production to achieve future cellulosic biofuel targets. Yet, recent survey results suggest landowners are hesitant to commit to new energy crops such as switchgrass. For example, a 2009 12-state survey summarized in Qualls et al. (2011) and Menard et al. (2011) found only 60% of respondents were somewhat to very interested in supplying switchgrass for bioenergy, even if profitable. This is an increase from the 2005 survey of Tennessee farmers where only 29.6% were interested and 46.7% were unsure and did not know if they would be willing to supply switchgrass if profitable (Jensen, et al., 2007). Variation in willingness to participate in biomass supply occurred for several reasons including operator age, environmental concerns, farming experience, market expectations, and opportunity cost of learning a new production process. Raising landowner awareness of the benefits from biomass production may be an important step in the feasibility of commercial scale production.

Public perception and consumer preferences influence the demand for biofuel. Negative publicity, including discussions surrounding the food-versus-fuel debate, impacted demand for first-generation biofuels. Further, some consumers have shown hesitancy to use biofuels due to unfamiliarity and uncertainty in long-run vehicle impacts. Beyond consumer preferences, future demand for biofuel also may be limited by competing energy technologies such as hydrogen, oil shale-derived fuels, tar sands-derived fuels, coal-to-liquids, and electricity (U.S. DOE, 2011a).

Probably the most pressing obstacle for development of the entire biofuel industry, both first- and second-generation, is the "blend wall." A blend wall is a theoretical limit on the quantity of ethanol that can be blended into the U.S. transportation fuel supply given regulatory blend limits. The previous regulatory cap of 10% ethanol blends (E10) for traditional vehicles limited ethanol blending to about 14 billion gallons per year, well below future mandate levels (Tyner, Brechbill, & Perkis, 2010). E85 has the potential to partially alleviate the blending wall constraint, but lack of refueling infrastructure has created limited demand for E85 relative to the flex-fueled fleet and below the supply potential of the ethanol industry. Less than 2% of all refueling stations are equipped to offer E85 (U.S. DOE, 2011b; Tyner, Brechbill, & Perkis, 2010). Further, survey estimates suggest upwards of 75% of flexible fuel vehicle owners may not know they can use E85 (Jessen, 2011).

In October 2010, the EPA increased the regulatory ethanol blend limit to 15% (E15) for cars and light trucks 2007 or newer. The E15 waiver was extended to cars and light trucks 2001 or newer in January 2011 (U.S. EPA, 2011). The increase in the regulatory limit to E15 will only provide temporary relief from the blend wall as mandated volumes will exceed the potential of E15 by 2015 (Tyner, Brechbill, & Perkis, 2010). Therefore, future RFS2 mandates will not be achievable without further increases in the regulatory blend limit, gasoline consumption, or E85 use (Duffield, Xiarchos, & Halbrook, 2008; Mallory, 2011).

2.8 Conclusions

This chapter provided an overview of the policies, potential, and challenges of the biofuel industry, with a focus on cellulosic biofuel. A historical account of biofuel policies evidenced the strong governmental support motivated by the concept of energy security and independence, potential rural economic development opportunities, and estimated environmental benefits associated with substituting biofuel for fossil fuels. Concerns regarding the ability of first-generation biofuels to provide a long-run alternative for fossil fuels turned attention and interest to second-generation biofuels. Biomass has the potential to significantly contribute to the U.S. energy sector with several alternative feedstock sources, but the second-generation biofuel industry has been slow to develop. Among other constraints, industry growth is limited by current production costs, uncertainty in future policies and market conditions, and the blend wall. With the motivating factors that fostered interest in development of a biofuel industry still relevant today and likely to remain relevant far into the future, issues surrounding commercial scale biofuel production will continue to be an important part of environmental and agricultural policy discussions.

CHAPTER 3. AN ECONOMIC EVALUATION OF U.S. BIOFUEL EXPANSION USING THE BIOFUEL BREAKEVEN PROGRAM WITH GHG ACCOUNTING

Summary results from this chapter are published in Rosburg and Miranowski (2011)

Abstract

To evaluate the long-run economic feasibility of local biofuel and biomass markets under various policy and market scenarios, an Excel-based program called The Biofuel Breakeven Program (BioBreak) is developed. The economic framework underlying BioBreak is described and the program is used to evaluate the economic feasibility of 14 local cellulosic biofuel markets that vary by feedstock and location. Program results suggest long-run cellulosic ethanol production is not sustainable without significant policies to support the industry or long-run oil prices of $135 - $170 per barrel. The BioBreak program results are extended using life-cycle analysis to derive the per unit cost of carbon savings from substituting cellulosic ethanol for conventional transportation fuel. This carbon price can be interpreted as the value of reduced emissions implied by current government intervention in the cellulosic ethanol industry, such as the RFS2 mandates. For the markets considered in this analysis, policies that sustain cellulosic ethanol production are found to value a reduction in carbon equivalents between $141 and $280 per metric ton, higher than most carbon prices discussed in the literature.

3.1 Introduction

The revised Renewable Fuels Standard (RFS2) mandates a minimum contribution from cellulosic biofuel to the U.S. transportation fuel mix starting in 2010 with increasing volume requirements up to 16 billion gallons in 2022. At the same time, the 2008 Farm Bill provides tax credits to cellulosic biofuel producers and subsidy payments to biomass suppliers. Even with mandated production and market-based incentives, the industry has been slow to develop, and cellulosic biofuel production has been limited to research labs and pilot plants. Without a commercial scale cellulosic biorefinery or biomass supply system, knowledge is limited regarding the costs and environmental impacts of supplying and converting cellulosic biofuel at the scale needed to meet current and future mandate levels. Consequently, economists and environmentalists have been tasked with evaluating potential economic and environmental implications of biofuel expansion, and more specifically, the impacts of meeting the RFS2 mandates.

Understanding the economic implications of biofuel expansion first requires an understanding of the economics of cellulosic biofuel production. For instance, can the production of cellulosic biofuel be a long-run breakeven proposition given available technology and market conditions? If not, what are the costs or market conditions needed to sustain a cellulosic biofuel market? These are the main questions addressed by the Biofuel Breakeven program (BioBreak). BioBreak is a flexible, Excel-based program developed to evaluate the long-run economic feasibility of local biofuel markets using breakeven models of the local feedstock supply system and biofuel refining process.[27] A local biofuel market will exist only if the biofuel processor can obtain sufficient feedstock and the local biomass market can deliver sufficient feedstock at a market price that allows both parties to break even in the long run. Given expected local market conditions derived from published literature estimates, BioBreak calculates the supplier and processor long-run breakeven values for biomass. Further, BioBreak derives the difference or "price gap" between the estimated supplier and processor breakeven prices. If the price gap is zero or negative, the local biofuel market is economically sustainable in the long run, and if positive, the price gap represents the market incentive needed to sustain the local market. This chapter provides an overview of the economic models underlying the BioBreak program and presents results from an application to 14 cellulosic ethanol markets that vary by feedstock and location.

To provide an alternative perspective of the price gap derived from BioBreak, we extend de Gorter & Just's (2009b) economic model of the transportation fuel sector with a biofuel blending

[27]The BioBreak program is an Excel-based spreadsheet program. The BioBreak program can be executed using either fixed coefficients or stochastic coefficients. The fixed coefficient version allows users to evaluate three cost scenarios, denoted as low, baseline, and high cost scenarios based on user-specified parameter and model assumptions. The stochastic option within BioBreak allows users to set distributional assumptions and conduct simulation through Crystal Ball® to account for parameter uncertainty.

mandate to include cellulosic biofuel production. This model provides the foundation to evaluate the carbon tax or price needed to satisfy biofuel blending mandates. The results from the BioBreak application are used in conjunction with greenhouse gas (GHG) emissions reductions derived from life-cycle analysis to identify the carbon tax or price needed to sustain local cellulosic ethanol markets in the long-run. This carbon price, which represents the per unit cost of carbon savings from substituting cellulosic ethanol for conventional fuel, can be interpreted as the value of reduced emissions implied by current government intervention in the cellulosic ethanol industry such as the RFS2 mandates.

Further applications of the BioBreak program can be found in the National Academies reports on Liquid Transportation Fuels from Coal and Biomass (ALTF, 2009) and the Renewable Fuels Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policies (NRC, 2011). The ALTF report uses a fixed coefficient version of BioBreak to derive low, baseline, and high cost estimates of cellulosic feedstock supply. The 2011 National Academies report utilizes the stochastic BioBreak program to estimate the cost and feasibility of cellulosic feedstock supply for select feedstocks and locations and presents an implicit valuation of carbon emissions reductions. A summary of the results presented in this paper are published in Rosburg & Miranowski (2011).

3.2 Economic framework for the BioBreak program

The BioBreak program is built using breakeven models for the local feedstock supply system and the biofuel refining process. The separation of analysis into biomass production and biomass processing is based on the assumption that the biorefinery will outsource biomass production to local producers.[28]

[28] The biorefinery is assumed to contract with several local suppliers to acquire enough biomass for commercial operation. With a competitive biomass market, the biorefinery cannot price discriminate and the price paid to all suppliers will equal the price paid for the last ton of biomass (i.e., marginal unit).

3.2.1 Biofuel processor

Since a commercial scale biorefinery is not currently available, the model of the biofuel refining process reflects a profit-maximizing biofuel processor deciding whether to invest in a proposed biorefinery. The biofuel processor makes the decision to invest based on the present value of expected net returns over the life of the biorefinery. Equation (1a) describes the present value of the stream of net returns π for a hypothetical biorefinery with plant capacity Q and expected plant life of T years. Net returns in each year are determined by revenue from biofuel production (R_t), biorefinery conversion and investment costs ($C_{R,t}$), and biofuel feedstock costs ($C_{F,t}$). For simplicity, equation (1c) defines $R(Q)$, $C_R(Q)$, and $C_F(Q)$ as the present value of biorefinery revenue, conversion and investment costs, and feedstock costs over the life of the plant, respectively.

$$\pi = E\sum_{t=1}^{T}\beta^{t-1}\left[R_t(Q) - C_{R,t}(Q) - C_{F,t}(Q)\right] \quad \textbf{(1a)}$$

$$= E\sum_{t=1}^{T}\beta^{t-1}R_t(Q) - E\sum_{t=1}^{T}\beta^{t-1}C_{R,t}(Q) - E\sum_{t=1}^{T}\beta^{t-1}C_{F,t}(Q) \quad \textbf{(1b)}$$

$$\equiv R(Q) - C_R(Q) - C_F(Q). \quad \textbf{(1c)}$$

If the present value of net returns is greater than or equal to zero ($\pi \geq 0$), the biofuel processor will build the proposed biorefinery. Given expected input and output prices and biorefinery technology, equation (1c) can be used to determine the optimal investment decision for a proposed biorefinery. Alternatively, equation (1c) can be used to determine the conditions (e.g., prices, technology) under which the biorefinery will break even in the long run (i.e., $\pi = 0$). This latter approach is used in the BioBreak program to estimate the breakeven price of feedstock. Given biorefinery technology, expected biorefinery returns, and conversion costs, the maximum feedstock cost the biorefinery can incur over the life of the biorefinery and breakeven is:

$$C_{F,Breakeven}(Q) = R(Q) - C_R(Q). \quad \textbf{(2)}$$

BioBreak makes assumptions regarding investor expectations to derive a single estimate of the maximum price the biofuel processor can pay per ton of feedstock in the long-run. First, the investor expects the biorefinery to operate at capacity every year within the plant life. Therefore, all fixed costs are converted into expected per gallon costs based on plant capacity. Second, the annual investment cost and corresponding investment cost per gallon are determined by an amortization of the biorefinery cost over the life of the plant. Third, the investor has complete knowledge of the plant technology, including required inputs per unit of output, and expects plant technology to remain constant over the life of the plant. In other words, the biorefinery cannot increase efficiency during the plant life without additional investment costs. Given market expectations and fixed biorefinery technology, BioBreak uses expected long-run conversion costs and returns per gallon to derive the processor's long-run breakeven price or derived demand (*DD*) for feedstock.

Equation (3) outlines a simplified version of the equation used in BioBreak to calculate the processor's long-run breakeven price or derived demand (*DD*) per ton of feedstock.[29]

$$DD = (P_{CF} * E_V + G_P + V_C + V_O - C_I - C_O) * Y_O. \quad \textbf{(3)}$$

Consistent with equation (2), biorefinery derived demand calculated by equation (3) equals total expected revenues per ton of feedstock converted to biofuel less non-feedstock conversion costs. The expected market price of biofuel is calculated as the energy equivalent price of conventional fuel, that is, the price fuel blenders would be willing to pay in a competitive market. In equation (3), P_{CF} denotes per gallon price of conventional fuel and E_V denotes the energy equivalent factor of conventional fuel to biofuel. Within BioBreak, the price of conventional fuel is a user-specified function of the price of oil (P_{oil}).[30] Beyond returns from the sale of each gallon of biofuel, the

[29] Although the calculation within brackets in equation (3) appears to be a simple linear equation, there are several exogenous factors underlying the parameters in the processor derived demand equation resulting in complicated, non-linear relationships. Exogenous factors include the price of energy, conversion technology, set of potential feedstocks, and capital investment factors.

[30] For the application to the cellulosic ethanol market in Section 3.4, the price of conventional gasoline is assumed to be a constant fraction of the price of oil, $P_{gas} = P_{Oil}/29$ based on historical trends (Elobeid, Tokogz, Hayes, Babcock, & Hart, 2006), but this relationship is flexible within BioBreak.

processor may also receive revenues from government incentives (G_P), for example, tax credits, coproduct production (V_C), and octane benefits (V_O) per gallon of processed biofuel. Non-feedstock biorefinery costs per gallon include amortized investment costs (C_I) and operating costs (C_O). The calculation within brackets in equation (3) provides the net return per gallon of biofuel above all non-feedstock costs. The conversion ratio of gallons of biofuel produced per dry ton of biomass (Y_O) converts per gallon net return prior to feedstock costs into the processor's *DD* per dry ton of feedstock.

The general format of equation (3) allows BioBreak to accommodate most biofuel platforms by categorizing platform-specific costs into the appropriate model parameters. The application in section 3.4 of BioBreak to the cellulosic ethanol industry uses data for a proposed biorefinery with a biochemical process – co-current dilute acid prehydrolysis and enzymatic hydrolysis. A distinguishing characteristic of a biochemical process is the use of enzymes to breakdown cellulose into simple sugars. As a result, enzyme costs are included in the operating costs for this analysis. Similarly, investment costs, other operating costs, and coproduct value (electricity) are consistent with a biochemical processing facility. Biorefineries utilizing other conversion platforms, such as a gasification or fast pyrolysis design, can be analyzed by BioBreak with minor adjustments to the interpretation and values included into each cost component.[31]

3.2.2 Biomass supply

Since the biorefinery will contract with local suppliers to acquire sufficient biomass for commercial-scale production, the model of biomass supply underlying BioBreak evaluates the long-run per ton feedstock cost faced by the biorefinery in a competitive local biomass market. With a competitive market, the biorefinery cannot price discriminate and the price paid to all suppliers will be the price paid for the marginal unit. The minimum payment a supplier of the marginal unit would

[31]Coefficients for biomass gasification, fast pyrolysis, and biochemical processes can be obtained from Swanson et al. (2009),Wright et al. (2009), and Kazi et al. (2010a), respectively.

accept is the value at which the supplier breaks even in the long run. The long-run breakeven price for the marginal unit will depend on all costs incurred, including land and biomass opportunity costs, to produce, store, and transport biomass to the biorefinery in the long run less any government incentives received for biomass supply (G_s) (e.g., production subsidies). Equation (4) outlines a simplified version of the equation used in BioBreak to estimate the long-run supply cost (*SC*) for the last ton of biomass to the biorefinery.[32]

$$SC = \{C_{ES} + C_{Opp} + C_{HM} + SF + C_{NR} + C_S + DFC + t * D\} - G_S \quad \textbf{(4)}$$

Depending on biomass feedstock, costs per dry ton include establishment and seeding (C_{ES})[33], land and biomass opportunity costs (C_{Opp}), harvest and maintenance (C_{HM}), stumpage fees (*SF*), nutrient replacement (C_{NR}), biomass storage (C_S), transportation fixed costs (*DFC*), and variable transportation costs calculated as the variable cost per mile (*t*) multiplied by the average hauling distance to the biorefinery (*D*). Average hauling distance is a function of the annual biorefinery biomass demand, annual biomass yield, and biomass density, and calculated using the formulation by French (1960) for a circular supply area with a square road grid.[34] Costs reported per acre are converted into per ton costs using the annual biomass yield per acre.

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[32] Similar to the equation for the biofuel processor's *DD* for feedstock, several exogenous factors (e.g., price of energy, conversion technology, feedstock, etc.) underlie the parameters in Equation (4) resulting in non-linear relationships between parameters.

[33] For perennial crops, the establishment and seeding cost is amortized over the expected life of the crop.

[34] Due to heterogeneity in non-transportation production costs within the capture region, BioBreak uses the average distance rather than the capture region distance. Although the transportation cost per unit of biomass will be higher at the edge of the capture region, the supply cost will not necessarily be strictly increasing with distance due to heterogeneity in production and opportunity costs. Even with higher transportation costs, a biomass supplier at the edge of the capture region with low production costs may be willing and able to supply biomass at a lower price than a biomass supplier with relatively high production costs located close to the biorefinery. Since BioBreak does not account for supplier heterogeneity within local markets, the program assumes the average hauling distance within the capture region is representative of the location of the last unit of biomass purchased by the biorefinery to meet the biorefinery feedstock demand. Using the capture region distance would provide the correct estimate of the supply cost if the last unit of biomass purchased by the biorefinery is located at the edge of the capture region, but would overestimate the supply cost in all other cases. Estimated biomass supply costs increase by $0.80-$2.70 per ton, depending on feedstock, if capture region distance is used instead of average hauling distance. Chapter 4 considers supplier heterogeneity within local markets and therefore uses capture region distance.

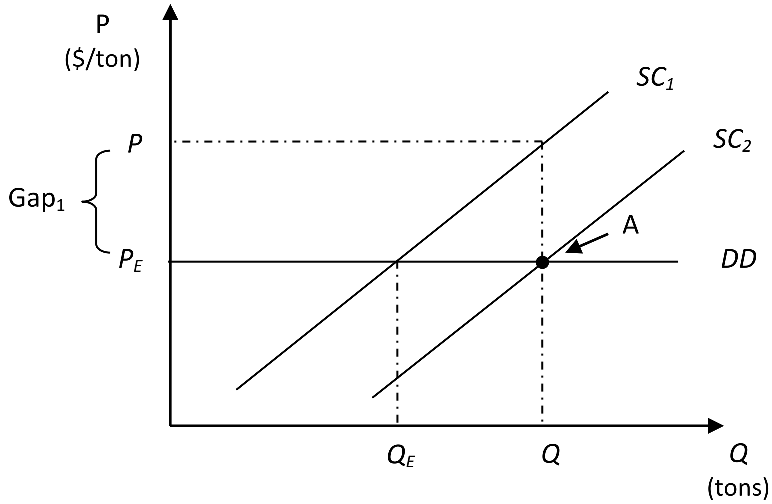
3.2.3 Biofuel market feasibility

A local biofuel market exists only if sufficient feedstock is deliverable at a market price that allows both parties to break even in the long run. In the absence of cellulosic biofuel mandates, economic sustainability of cellulosic biofuel markets depends on the relationship between the long-run price the local biomass producers will accept for biomass (*SC)* and the long-run price the biofuel processor can pay for biomass (*DD*). Given market conditions, BioBreak provides the difference or "price gap" between the biomass supply price and processor *DD* (i.e., price gap = *SC* – *DD*). If the price gap is zero or negative, the local biofuel market is economically sustainable in the long run, and if positive, the price gap represents the gap that needs to be closed to sustain the local biofuel market.

BioBreak derives point estimates of the *SC* and *DD* values and the price gap between them for a fixed plant capacity and local feedstock market. Figure 3.1 provides a graphical depiction of the price gap derived by BioBreak. Although illustrated as a horizontal line, the *DD* for feedstock calculated by the BioBreak program is a point estimate at A, that is, the price the processing plant can pay per ton of feedstock if operating at capacity *Q*. Otherwise, the plant will not operate in the long run.[35] Consider the two upward sloping biomass supply curves in Figure 3.1. First, SC_1 intersects the *DD* curve but at a feedstock quantity less than necessary to operate the biorefinery at capacity and still break even in the long run. For a biomass market with SC_1, BioBreak would calculate the price gap = $(P - P_E) > 0$ at feedstock quantity *Q*. Alternatively, if SC_2 was the supply curve for the biomass market which intersects *DD* at point A, the price gap = $(P – P_E) = 0$ at quantity *Q*.

[35] The BioBreak model presented here assumes a fixed plant capacity and does not consider smaller or larger biorefineries. Implications of this assumption are discussed in Section 3.4. Chapter 4 considers location-specific cost-minimizing biorefinery capacity given local biomass and biorefinery production conditions.

Figure 3.1 – Price gap estimated by BioBreak



3.2.4 Mandated biofuel production and waiver credits

In terms of the cellulosic biofuel blending mandates outlined in the U.S. RFS2, the price gap estimates from BioBreak provide an estimate of the potential costs of meeting mandated production if mandates are fully enforced. Yet, provisions within the Energy Independence and Security Act of 2007 (EISA) allow for the EPA administrator to waive completely or in part the RFS2 cellulosic mandate if it is determined "implementing the requirement would severely harm the economy or the environment, or that there is inadequate domestic supply to meet the requirement" (RFA, 2010a). When a portion of the cellulosic biofuel mandate is waived, the EPA is required to make cellulosic waiver credits available for purchase by obligated parties which can be used to meet the revised mandated volumes in lieu of blending cellulosic biofuel.[36] With waiver credits available, obligated parties will minimize losses through the purchase of waiver credits and/or investment in biofuel

[36] Waiver credits are priced at the maximum of "(i). $0.25 per cellulosic biofuel waiver credit, adjusted for inflation in comparison to calendar year 2008; or (ii) $3.00 less the wholesale price of gasoline per cellulosic biofuel waiver credit, adjusted for inflation in comparison to calendar year 2008" (U.S. EPA, 2010b, p. 14892). The wholesale price of gasoline is calculated as the average refiner's monthly bulk sale price over the previous 12 months as of September 30 prior to the compliance year. Waiver credits were available for $1.56 per gallon in 2010 and $1.13 per gallon in 2011 (U.S. EPA, 2010b; U.S. EPA, 2010a). The 2012 waiver credit price is significantly lower at $0.78 per gallon (U.S. EPA, 2012a).

production. The price gap derived from BioBreak will quantify the cost to obligated parties to meet mandated RFS2 blend volumes only if the price gap is less than or equal to the waiver credit price. If the price gap is higher than the waiver credit price, the revised mandate will be met with the purchase of waiver credits. In other words, the economic costs of meeting mandated production will be capped at the cost of purchasing waiver credits. BioBreak provides an option to evaluate the cost of meeting mandated production with and without a user-specified price for waiver credits.

3.3 Simplifying assumptions

The BioBreak estimates are based on a number of assumptions. Here, we address three key assumptions. A full discussion can be found in Miranowski & Rosburg (2010b).

First, BioBreak assumes a fixed relationship between gasoline and ethanol based on the energy equivalence of ethanol to gasoline. A fixed relationship presumes gasoline and ethanol are perfectly substitutable in consumption and ethanol does not require an extra marketing cost. De Gorter & Just (2009a; 2009b) argue perfect consumption substitutability between ethanol and gasoline is a realistic assumption for low level blends of ethanol, such as 10 or 15 percent, and for E85 in flex fuel vehicles but may not be a valid assumption for differentiated products or in the presence of the “blending wall” (i.e., the regulatory limit on the amount of ethanol that can be blended with gasoline and supplied through traditional pumps). BioBreak evaluates the economic feasibility of cellulosic biofuel markets in the absence of the blending wall constraint but we acknowledge this may be another limiting factor to future biofuel market development.

Second, BioBreak does not incorporate policy uncertainty and is not capable of analyzing short-run or temporary program impacts in its current form. The program application in Section 3.4 considers the impacts of policy incentives but assumes incentives would be provided for the life of the biorefinery. Perhaps of greater concern is uncertainty regarding enforcement of RFS2 mandates. Since the EPA conducts an annual evaluation of the cellulosic ethanol industry and provides revised mandates if deemed necessary, potential biofuel processors face uncertainty regarding the future biofuel market. The biofuel processor may require a minimum biorefinery return, or a 'risk premium,' to induce investment. A risk premium is not considered in the application of BioBreak presented here, but a minimum biorefinery return could be incorporated into the model without difficulty.

Third, BioBreak does not consider the impact of energy price uncertainty on biofuel investment. If potential investors require a risk premium due to uncertainty in long-run energy markets, the actual *DD* will be lower and price gap higher than the estimates provided by BioBreak. With energy market uncertainty, a price gap estimate below zero will satisfy a necessary condition for development of a cellulosic biofuel market, that is, both biomass supplier and processor break even in the long run, but may not be sufficient to induce investment.

3.4 Application of the BioBreak program

We apply BioBreak to estimate the feasibility of cellulosic ethanol markets using a biochemical refining process (dilute acid prehydrolysis with saccharification and cofermentation) and seven potential feedstocks (corn stover, switchgrass, *Miscanthus*, wheat straw, alfalfa, farmed tress, and forest residue). Corn stover is evaluated for land in continuous corn production (CC) and land in a corn-soybean rotation (CS).[37] We also consider a four-year corn stover/alfalfa rotation with two years in each crop (i.e., CCAA). Switchgrass is evaluated in three markets with characteristics considered representative of three regions: Midwest (MW), South Central (SC), and Appalachian (App). *Miscanthus* is evaluated for the Midwest and Appalachian regions, while corn-stover and wheat straw are assumed to be produced on current cropland base in the Midwest and Pacific Northwest (PNW) regions, respectively. To account for the heterogeneity in Midwest land quality,

[37] Continuous corn production is less profitable than a corn-soybean rotation with and without stover harvest because of the yield penalty associated with continuous corn (Iowa State University - University Extension, 2010; Purdue University - Purdue Extension, 2009). Yet, continuous corn provides higher stover density in a given local market over two years and lowers biomass transportation costs.

switchgrass and *Miscanthus* are evaluated from biomass markets with high quality (HQ) and low quality (LQ) Midwest cropland.[38] In total, we consider 14 biomass feedstock/market regions.

The biorefinery technology and costs used in this application are based on the techno-economic analysis by Kazi et al. (2010b) for a 54 million gallon per year (mgy) biorefinery. Although we do not consider larger or smaller biorefineries in this application, a brief discussion of the relationship between biorefinery capacity and production costs is warranted. Cellulosic biofuel production faces an economic trade-off between biorefinery economies of scale and biomass procurement diseconomies. As biorefinery capacity increases, biorefinery economies of scale result in decreasing average processing costs per gallon, at least up to a point. At the same time, the increase in feedstock demand for a larger biorefinery requires feedstock to be transported from more distant locations and/or the biorefinery to incentivize additional landowners within the capture region to supply biomass. Either method to increase feedstock supply increases the average feedstock cost per gallon. Given the complexity of the relationship between economies of scale and diseconomies of biomass procurement, an analysis of alternative biorefinery capacities is beyond the scope of the BioBreak model presented here.[39]

Without data from a commercial scale biorefinery or biomass supply system, uncertainty exists regarding input values for the BioBreak program. BioBreak provides the option to estimate breakeven values with fixed parameters or with stochastic simulation based on user-specified parameter distributions.[40] This analysis uses the stochastic simulation feature. Model parameter distributions are based on observed values in published literature which exhibit significant variation. Published literature values were updated to 2007 using USDA National Agricultural Statistics Service

[38] The two land quality scenarios in the Midwest were constructed to distinguish between valuable cropland with high opportunity cost in terms of foregone cash crop production and lower opportunity land such as cropland pasture.

[39] Chapter 4 considers the tradeoff between processing economies and biomass procurement diseconomies.

[40] BioBreak uses Oracle's spreadsheet-based program Crystal Ball® for stochastic simulation. Stochastic simulation allows for parameter variability, parameter correlation, and sensitivity testing not available in the fixed-parameter specification.

(NASS) prices (2007a; 2007b) and distributional assumptions were verified with industry information when available. The stochastic simulation approach used in BioBreak allows us to capture the large variability in the research estimates for model parameters. The program results discussed in the following section are based on the mean values from stochastic simulation.

For the long-run price of oil, we chose to evaluate scenarios rather than specify a distribution or a single value. The price of oil is variable and determines the price of ethanol in BioBreak. In July 2008, the price of oil escalated to $145 per barrel but dropped to $30 per barrel in December 2008. This analysis considers three long-run oil price scenarios: $50 per barrel, $100 per barrel, and $150 per barrel. Similarly, technological uncertainty of cellulosic ethanol production provides a range of estimates for the ethanol conversion ratio. Based on the range of conversion ratios reported in the literature (see Appendix Table B.2.1), a biomass-to-ethanol conversion ratio with mean value of 70 gallons per dry ton is assumed to be representative of current and near future technology. At the assumed baseline conversion rate of 70 gallons per dry ton and an annual capacity of 53.4 mmgy, the biorefinery will process approximately 771,750 tons of feedstock per year or 2,205 dry tons per day assuming an online time of 350 days per year. The impact of an increase in the mean conversion ratio to 80 gallons per dry ton is considered within the sensitivity analysis. Appendix B.1 provides a brief summary for each of the model parameter assumptions including parameter distribution assumptions, and Appendix B.2 provides summary tables with literature estimates used to develop distribution assumptions.

For comparison purposes, we specify a “baseline” scenario and provide sensitivity results relative to the baseline scenario. The baseline scenario consists of no fiscal policy incentives for biofuel production including no tax credits or payment programs, a long-run oil price of $100 per barrel, and a conversion rate of 70 gallons per dry ton of feedstock.

3.4.1 Baseline results

Given the parameter distribution assumptions, the supply cost for the last short ton of biomass delivered to the local biorefinery ranges between $72 per ton for wheat straw in the PNW to $130 per ton for switchgrass grown on high quality Midwest cropland.[41] Table 3.1 provides the long-run *SC* for biomass delivered to the local refinery for all 14 local feedstock markets considered in this analysis.[42] Stover harvested from Midwest cropland in continuous corn production is significantly more expensive than stover harvested from land in a corn-soybean rotation. The benefit of a smaller biomass supply region from continuous corn production, that is, lower transportation costs, is more than offset by the lost net returns from switching from a corn-soybean rotation to continuous corn. Local market characteristics also play a significant role. Switchgrass and Miscanthus grown on high quality Midwest cropland have relatively high costs due to high land opportunity costs and lower yields relative to the same feedstock grown in the Appalachian and South Central regions.

For the 14 feedstock/regions considered in this analysis, long-run cellulosic ethanol production is not sustainable without significant government intervention in the baseline scenario. As shown in Table 3.1, the long-run biomass supply cost (*SC*) exceeds the processor's long-run derived demand price (*DD*) for all markets. The difference between the supply cost and derived demand price, denoted as the price gap, ranges from $57 per ton of wheat straw to $116 per ton of switchgrass grown on high quality Midwest cropland. The estimated price gaps represent the costs to sustain markets and are equivalent to a per gallon ethanol cost between $0.82 and $1.65.[43]

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[41] Relative to other feedstocks, wheat straw grown in the Pacific Northwest has very low opportunity cost and nutrient replacement cost. Wheat straw also is assumed to be supplied from previously established stands, resulting in no establishment or seeding costs.

[42] The parameter draws and calculations were repeated one thousand times resulting in one thousand values for *SC*, *DD*, and the price gap (*SC* – *DD*) for each scenario. The values reported are the mean values over the thousand calculations for each feedstock.

[43] Estimates presented here are on a per gallon ethanol basis. The estimated price gaps for the baseline scenario are equivalent to a cost between $1.23 and $2.48 per gallon gasoline equivalent.

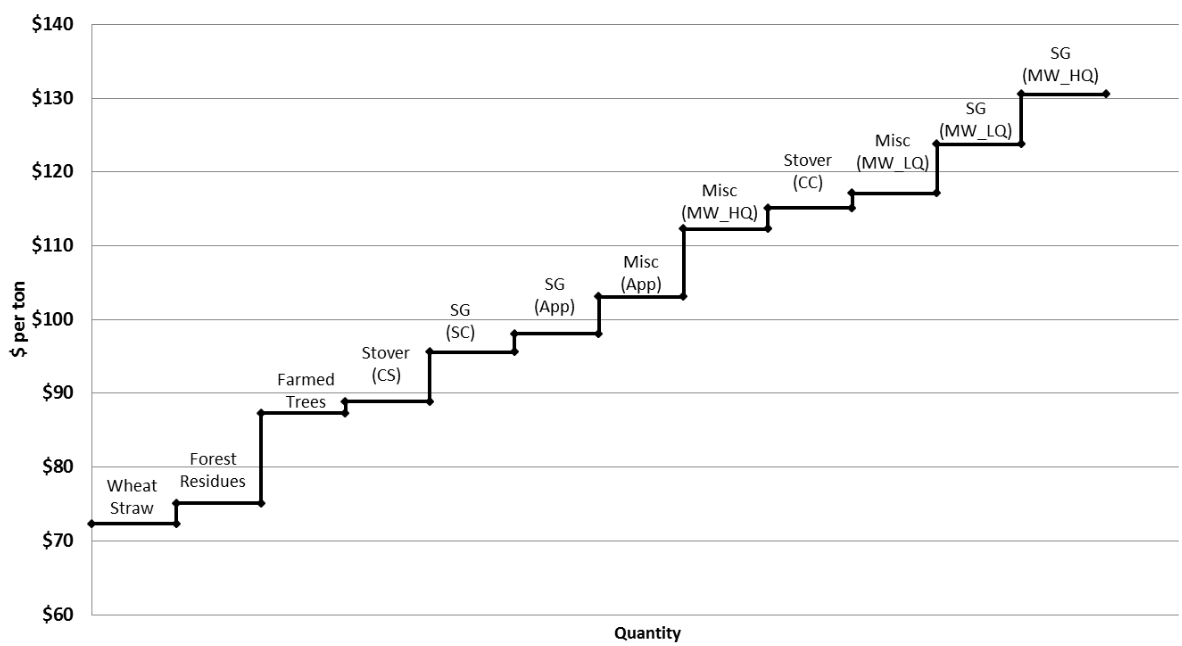
Table 3.1 – Supply cost, derived demand, and price gap for a 53.4 mgy biorefinery
($ per ton feedstock)
(Baseline scenario, 70 gal/dry ton, 2007$)

	SC	***DD***	**Price gap**
Stover (CC)	$115	$13	$102
Stover (CS)	$89	$13	$76
Stover/Alfalfa	$89	$14	$75
Alfalfa	$115	$15	$100
Switchgrass (MW HQ)	$130	$15	$116
Switchgrass (MW LQ)	$124	$15	$109
Switchgrass (App)	$98	$15	$83
Switchgrass (SC)	$96	$15	$81
***Miscanthus* (MW HQ)**	$112	$15	$97
***Miscanthus* (MW LQ)**	$117	$15	$102
***Miscanthus* (App)**	$103	$15	$88
Wheat straw	$72	$15	$57
Farmed trees	$87	$12	$75
Forest residues	$75	$12	$63

Note: Reported *SC*, *DD*, and price gap estimates are mean values from BioBreak simulation.

A step-wise supply curve can be derived from the *SC* results similar to the supply curves reported in the ALTF report (2009). Figure 3.2 presents a step supply curve based on the local feedstock markets considered in this analysis with the exception of alfalfa and stover/alfalfa.

Figure 3.2 – Step biomass supply curve



3.4.2 Sensitivity analysis

The breakeven values and resulting price gaps presented in Table 3.1 are sensitive to assumptions and parameters used in the analysis. In the following, we present sensitivity analysis relative to the baseline scenario for the price of oil, conversion technology, and current and potential policy incentives.

Oil price

The price of oil impacts both the processor's *DD* price and feedstock *SC*. An increase in the energy price will increase biomass input costs but also increase the biofuel price or processor revenue. Over the range of oil prices considered in this analysis, a change in the price of oil has a relatively minimal impact (< 5%) on the biomass supplier's nutrient replacement, harvest, and transportation costs. Compared to the baseline scenario ($100/barrel), the low ($50/barrel) and high oil cost ($150/barrel) scenario decrease and increase the long-run feedstock supply cost by approximately $4 per ton, respectively. Given the small magnitude of these impacts, sensitivity analysis will focus on the impact of the long-run price of oil on the processor's *DD* price.

Since the price of ethanol is tied directly to the price of oil, any increase in the price of oil results in a decrease in the price gap. The results in Table 3.1 are based on a long-run oil price of $100 per barrel. If the long-run expected oil price is $50 per barrel, the price gap increases to range between $138 and $196 per ton of biomass (Table 3.2, Column 2) ($1.97 - $2.80/gallon). At a long-run oil price of $150 per barrel, cellulosic biofuel markets are sustained for stover (CS), stover/alfalfa, switchgrass (SC), wheat straw, farmed trees, and forest residues (Table 3.2, Column 3).

Table 3.2 – Price gap for a 53.4 mgy biroefinery by oil price, technology, and policy scenario ($ per ton feedstock)
(Baseline assumptions unless noted otherwise, 2007$)

	Baseline ($100 oil)	$50 oil	$150 oil	80 gal/ton conversion ratio	Tax credit
Stover (CC)	$102	$182	$21	$92	$31
Stover (CS)	$76	$156	0	$66	$5
Stover/Alfalfa	$75	$156	0	$66	$5
Alfalfa	$100	$181	$20	$91	$30
Switchgrass (MW HQ)	$115	$196	$35	$105	$45
Switchgrass (MW LQ)	$109	$189	$29	$99	$38
Switchgrass (App)	$83	$164	$3	$74	$12
Switchgrass (SC)	$81	$161	$0	$71	$10
***Miscanthus* (MW HQ)**	$98	$178	$17	$88	$27
***Miscanthus* (MW LQ)**	$102	$183	$22	$92	$32
***Miscanthus* (App)**	$89	$169	$8	$79	$18
Wheat straw	$57	$138	$0	$48	$0
Farmed trees	$75	$156	$0	$66	$5
Forest residues	$63	$143	$0	$54	$0

Note: Price gap estimates censored below at $0.

Given long-run oil price uncertainty, we also calculate the expected long-run oil price needed to sustain each biomass market or the oil price which eliminates the price gap. Without government incentives, the long-run oil price needed to sustain cellulosic ethanol markets ranges between $136 per barrel for a wheat straw market in the PNW to $172 per barrel for switchgrass on Midwest cropland (Table 3.3, Column 1).

Conversion technology

The baseline results assume a conversion ratio of 70 gallons per dry ton of biomass for all feedstocks, but conversion technological advances are expected to increase this ratio. An increase in the biomass conversion ratio increases the biorefinery net returns per unit of feedstock and decreases the price gap. Table 3.2 provides price gap sensitivity to the higher conversion ratio of 80 gallons per dry ton. Assuming $100 per barrel oil and the higher conversion ratio, the price gap decreases to range between $48 and $105 per ton (Table 3.2, Column 4).

Table 3.3 – Long-run oil price needed to sustain a biomass market for a 53.4 mgy biorefinery ($ per barrel)
(Baseline scenario unless noted, 70 gal/dry ton, 2007$)

	No policy incentive	Tax credit	Tax credit & CHST payment
Stover (CC)	$164	$120	$63
Stover (CS)	$147	$103	$47
Stover/Alfalfa	$147	$103	$47
Alfalfa	$163	$119	$63
Switchgrass (MW HQ)	$172	$128	$72
Switchgrass (MW LQ)	$168	$124	$68
Switchgrass (App)	$152	$108	$52
Switchgrass (SC)	$150	$106	$50
***Miscanthus* (MW HQ)**	$161	$117	$61
***Miscanthus* (MW LQ)**	$164	$120	$64
***Miscanthus* (App)**	$155	$111	$55
Wheat straw	$136	$92	$36
Farmed trees	$147	$103	$47
Forest residues	$139	$96	$39

Fiscal policy incentives

Policy incentives to either biomass suppliers or biofuel processors will decrease the price gap. The impacts of two policy incentive scenarios on the baseline model results are considered. The first scenario maintains baseline assumptions and adds the $1.01 per gallon tax credit provided by the 2008 Farm Bill to cellulosic biofuel producers. The second policy scenario includes the tax credit plus the biomass collection, harvest, storage, and transportation (CHST) matching payment up to $45 per ton of biomass also provided in the 2008 Farm Bill as part of the Biomass Crop Assistance Program. Even though the CHST payment program was written as a two-year program and the producer's tax credit is up for renewal in December 2012, CHST payments and tax credits are treated in this illustration as if these are long-term policy incentives.

With a long-run tax credit and a long-run oil price of $100 per barrel, local biofuel markets are sustainable for wheat straw and forest residues (Table 3.2, Column 5). The remaining markets have a price gap between $5 and $45 per ton ($0.06-$0.64/gallon). Comparing the first and second column in Table 3.3, the tax credit has essentially the same impact as a $44 per barrel long-run oil price increase. With a long-run CHST payment program in addition to the tax credit, the price gap is eliminated for all 14 markets in the baseline scenario ($100 per barrel oil).

Waiver credits

The results presented so far provide estimates of the economic costs to sustain local biomass markets without the availability of waiver credits, and therefore represent the cost to meet fully enforced cellulosic biofuel mandates. If the EPA revises the mandates and provides obligated parties the option to purchase waiver credits, the economic costs of meeting the RFS2 will be capped at the cost of purchasing waivers to fulfill volume requirements. The EPA offered waiver credits at a price of $1.56 per gallon in 2010 and $1.13 per gallon in 2011 (U.S. EPA, 2010; U.S. EPA, 2010). The waiver credit price for 2012 is significantly lower at $0.78 per gallon (U.S. EPA, 2012a) and obligated parties will not invest in cellulosic biofuel production unless their expected net losses are less than $0.78 per gallon.

To evaluate the potential impact of revised mandates and availability of waiver credits, BioBreak provides output based on a trigger value set at the cost of purchasing waiver credits in lieu of production. If the estimated net losses fall below the trigger value, the program indicates the biorefinery would not operate since the obligated party would opt to purchase waiver credits in lieu of production.

Table 3.4 provides estimates of per gallon net losses for each local market under three oil price scenarios. At the baseline long-run oil price of $100 per barrel and the 2012 waiver credit price, the purchase of waiver credits would be the cost-minimizing option over all feedstock and location combinations. At the 2011 waiver credit price ($1.56 per gallon), investment in biofuel production would be the cost-minimizing decision for the local biomass markets utilizing stover from a corn-soybean rotation, a stover/alfalfa rotation, wheat straw, farmed trees, and forest residues. The purchase of waiver credits would be the cost-minimizing option over all other feedstock and location combinations. At a long-run oil price of $50 per barrel, the cost-minimizing option for all local markets is to purchase waiver credits in lieu of production at any of the 2010 – 2012 waiver credit prices. On the other hand, production is the cost-minimizing option for all waiver credit prices at a long-run oil price of $150 per barrel.

Table 3.4 – Net losses per gallon of cellulosic ethanol production
(Baseline scenario unless noted otherwise)

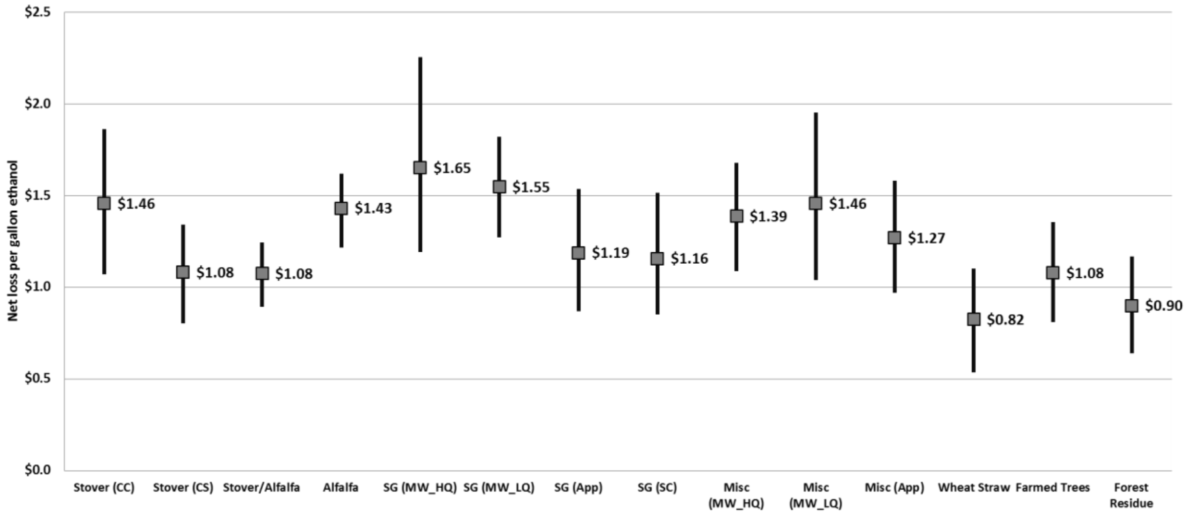
	$50 oil	**$100 oil (Baseline)**	**$150 oil**
Stover (CC)	$2.61 W	$1.46 W	$0.31
Stover (CS)	$2.23 W	$1.08 W	-$0.07
Stover/Alfalfa	$2.23 W	$1.08 W	-$0.07
Alfalfa	$2.58 W	$1.43 W	$0.28
Switchgrass (MW HQ)	$2.80 W	$1.65 W	$0.50
Switchgrass (MW LQ)	$2.70 W	$1.55 W	$0.40
Switchgrass (App)	$2.34 W	$1.19 W	$0.04
Switchgrass (SC)	$2.31 W	$1.16 W	$0.01
***Miscanthus* (MW HQ)**	$2.53 W	$1.39 W	$0.24
***Miscanthus* (MW LQ)**	$2.61 W	$1.46 W	$0.31
***Miscanthus* (App)**	$2.42 W	$1.27 W	$0.12
Wheat Straw	$1.97 W	$0.82 W	-$0.32
Farmed Trees	$2.22 W	$1.08 W	-$0.07
Forest Residues	$2.05 W	$0.90 W	-$0.25

Note: A negative value denotes a production process with positive long-run net returns.
W If available, waiver credits would be purchased in lieu of production at the 2012 cost of waivers ($0.78/gallon).

Parameter variability

As evidenced by the wide range in published estimates of cellulosic ethanol production costs and technology (see Appendix B.2), there is significant uncertainty in the cellulosic ethanol industry. To account for this uncertainty, we used the stochastic feature provided by BioBreak which allows users to specify model parameter distributions rather than point estimates. Figure 3.3 provides a visual depiction of the sensitivity of the net losses per gallon of ethanol to the distributional assumptions. The 90% confidence intervals in Figure 3.3 are constructed based on the 5th and 95th percentile draws in the BioBreak Monte Carlo simulation.

Figure 3.3 – 90% confidence interval for net losses per gallon of cellulosic ethanol production



3.4.3 Comparison with previous literature

With mandated cellulosic biofuel production and uncertainty regarding the feedstock supply system, a large body of literature has provided estimates of the costs or impacts of commercial-scale biomass supply. Biomass cost estimates vary based on model assumptions including biorefinery size, location, land quality, and cost aggregation, for example farm-gate or delivered. While some studies, such as the BioBreak program, break down each cost component, others focus on the market impacts of biomass supply and assume biomass cost values based on previous literature. Table 3.5 provides a comparison of the baseline *SC* value to the range of values presented in the literature. Since the underlying assumptions vary by study, Appendix B.3 provides a summary table of literature estimates and corresponding assumptions. The baseline *SC* values fall in the upper range reported in the literature for most feedstocks with the exception of wheat straw. The literature ranges presented in Table 3.5 are based on the values reported in the literature and are not updated to a consistent dollar value. Due to differences in delivery and storage assumptions, energy costs, and biotechnology over time, the reader should use caution when comparing values across studies.

Table 3.5 – Comparison of baseline *SC* and values reported or assumed in literature

	Literature range ($/ton)	**Baseline *SC***
Alfalfa	54-140	115
Biomass/energy crops	10- >115	--
Miscanthus	24-212	103-117
Grasses (mixed and native prairie)	40-854	--
Stover (including cobs)	20-120	89-115
Straw (including wheat straw)	27-60	72
Switchgrass	23-486	96-130
Wood	10-91	75-87

Table 3.6 compares the baseline *SC* values to three studies published in 2010. Jain, Khanna, Erickson, & Huang (2010) derive switchgrass and *Miscanthus* farm-gate breakeven prices (i.e., excludes transportation) across Midwest states using an integrated biophysical model. The authors evaluate a low and high cost scenario for each state based on different levels of establishment ease, nutrient requirements, harvesting costs, and dry matter loss. In the low cost scenario, the *Miscanthus* farm-gate breakeven price ranges between $48 and $139 per dry ton while the switchgrass farm-gate breakeven ranges between $80 and $144 per dry ton. In the high cost scenario, *Miscanthus* and switchgrass farm-gate breakeven prices range between $77 - $212 and $107 - $171 per dry ton, respectively. Removing transportation-related costs, the baseline farm-gate *SC* values derived from BioBreak for *Miscanthus* ($99) and switchgrass ($107 - $109) grown in the Midwest fall within the estimated range for both the low and high cost scenarios in Jain et al. (2010).

The second paper, James et al. (2010), derives the breakeven price to make six biomass feedstocks competitive with continuous corn production in the Great Lakes region. The breakeven price (sensitivity range) that would make the feedstock equally profitable to continuous corn production is $104 per ton ($41 - $167) for switchgrass, $180 per ton ($161 - $198) for Miscanthus using current technology, $40 per ton ($24 - $60) for Miscanthus assuming a significant rhizome cost reduction, and $98 per ton ($60 - $135) for poplar. The baseline *SC* values derived from BioBreak for switchgrass and Miscanthus on high quality land in the Midwest are $130 and $112 per ton while the estimate for farmed trees is $87 per ton. These estimates fall within the corresponding breakeven range reported by James et al. (2010).

Tyner, Brechbill, & Perkis (2010) provide best-guess estimates of the farm-gate feedstock costs for corn stover, switchgrass, Miscanthus, short-run woody crops, and forest residues. Reported farm-gate feedstock costs were between $50 - $70 per dry ton for corn stover, $65 - $85 per dry ton for switchgrass, $60 - $80 per dry ton for Miscanthus, $50 - $60 per dry ton for short-run woody crops, and $45 per dry ton for forest residues (Tyner, Brechbill, & Perkis, 2010). The baseline farm-gate *SC* values derived from BioBreak are above or on the upper end of the range reported by Tyner, Brechbill, & Perkis (2010) with the exception of forest residues. We are unable to determine the source of the discrepancy between the baseline *SC* values and those reported by Tyner, Brechbill, & Perkis (2010) for most feedstocks as the authors do not provide details regarding their cost assumptions. One discrepancy we can address is the difference in the corn stover cost estimates. Tyner, Brechbill, & Perkis (2010) argue opportunity cost should not be included in corn stover costs since it is a byproduct of corn production. While we do not include an opportunity cost for stover from a corn-soybean rotation, we do for stover from continuous corn production equal to lost profits for switching from a corn-soybean rotation. This explains why the baseline farm-gate *SC* value for corn stover from land in a corn-soybean rotation ($67) falls within the range estimated by Tyner, Brechbill, & Perkis (2010), but the baseline estimate of stover from continuous corn production is higher than their reported range.

Table 3.6 – Comparison of baseline biomass *SC* values to three 2010 publications

	Jain et al. (2010)[a] Farm-gate	**James et al. (2010)** [b]	**Tyner et al. (2010)** Farm-gate	**Mean baseline *SC*** (Farm-gate)
Stover	--	--	$50-70	$89-$116 ($67-97)
Miscanthus	$48-139 (low) $77-212 (high)	$180 (current) $40 (future)	$60-80	$102-115 ($89-99)
Switchgrass	$80-131 (low) $107-171 (high)	$104	$65-85	$93-128 ($77-109)
Farmed trees	--	$98 (poplar)	$50-60	$86 ($68)
Forest residues	--	--	$45	$73 ($38)

[a]Jain et al. (2010) estimates are for Midwestern states only.
[b]Values presented for James et al. (2010) are the reported 'baseline' values.

3.5 Implicit carbon price

The results from BioBreak can also be used to calculate an implicit carbon price embodied in cellulosic biofuel. Reducing greenhouse gas (GHG) emissions by substituting cellulosic biofuel for conventional fuel is frequently discussed as justification for cellulosic biofuel policies. In particular, provisions in the RFS2 outline minimum GHG reduction standards for each type of biofuel relative to 2005 gasoline or diesel. In terms of market failure theory, cellulosic biofuel creates social benefits external to producers' and consumers' decision processes. Producers and consumers will realize the full costs of cellulosic biofuel production and consumption, but they do not consider the social value of reduced GHG emissions from biofuel.[44] As a result, biofuel production would be lower than the socially optimal level, that is, below the quantity where the added benefits equal the added costs, unless producers and consumers are forced by mandates or receive an incentive to internalize GHG benefits.

We extend an economic model of a biofuel blending mandate to develop a measure for the carbon tax that would induce production of mandated cellulosic biofuel volumes if conventional fuel producers were taxed based on GHG emissions relative to cellulosic biofuel. This carbon tax, which represents the per unit cost of reduced GHG emissions from substituting cellulosic ethanol for

[44]Although biofuels also produce GHG emissions (i.e., externality-producing output), with multiple activities generating externalities the socially optimal solution may result in "substituting more of a slightly polluting activity for another that is highly damaging" (Baumol & Oats, 1975, p. 98).

conventional fuel, could be interpreted as the value of reduced GHG emissions embodied in cellulosic ethanol. By combining BioBreak price gap estimates with data on GHG emissions reduction, we compute the cost of GHG emissions reduction implied by mandated biofuel production.

3.5.1 Economic model of cellulosic biofuel blend mandate

We extend the graphical framework by de Gorter & Just (2009b) for a transportation fuel sector with a biofuel blending mandate to include cellulosic biofuel production. For simplicity, all domestic cellulosic biofuels are represented by a single supply curve, S_{CB}.[45] Following the argument of Babcock, Marette, & Tréguer (2011), cellulosic biofuel expansion is not assumed to displace first-generation biofuels, such as corn ethanol, but rather compete with all transportation fuels since "owners of existing conventional biofuel plants will continue to operate their plants if it is profitable to do so" (pg. 715).[46] As a result, competing transportation fuels can be represented by a single supply curve S_F. Since conventional gasoline provides the dominate portion of the competing transportation fuel, this class of fuels will be referred to as 'conventional fuel' for the remainder of the model discussion. Domestic market demand is represented by a single curve D_F where cellulosic biofuel and conventional fuel are assumed to be perfect substitutes in consumption on an energy equivalence basis.

The appropriateness of perfect consumption substitutability between ethanol and conventional fuel warrants additional explanation. As mentioned in Section 3.3, perfect consumption substitutability between ethanol and gasoline may be a realistic assumption for low level blends of ethanol, such as 10 or 15 percent, and for E85 in flex fuel vehicles but may not be a logical assumption for differentiated products (de Gorter & Just, 2009a; 2009b). Substitutability of ethanol

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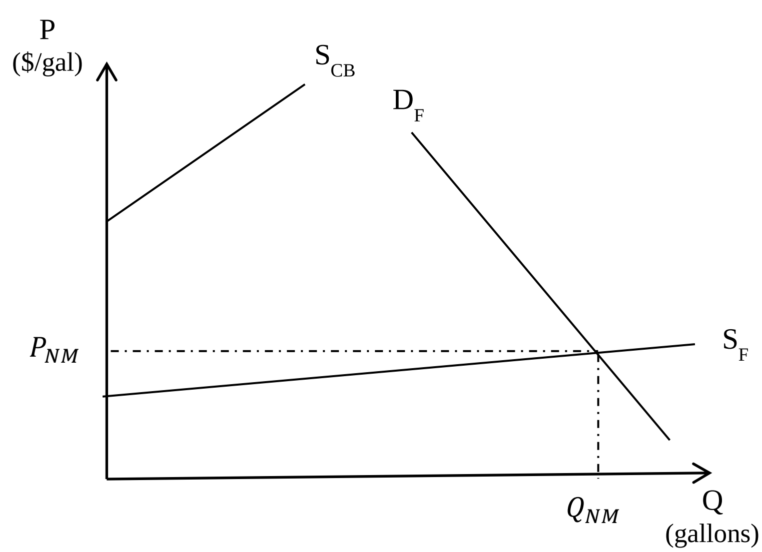
[45] Cellulosic biofuel imports are not considered. Currently, imported cellulosic biofuel can be used to meet the undifferentiated portion of the RFS2 advanced biofuel mandate but does not qualify for the cellulosic biofuel mandate, the focus of this analysis.

[46] Although corn ethanol also has a biofuel mandate under the RFS2, the impacts of corn ethanol policies have been widely studied and are outside the scope of this analysis. The reader should refer to the following papers for additional information regarding the welfare and market implications of corn ethanol policies: Babcock, Barr, & Carriquiry (2010), Babcock et al. (2011), Cui, Lapan, Moschini, & Cooper (2010), de Gorter & Just (2009b; 2009a), Lapan & Moschini (2009), and McPhail & Babcock (2008).

for gasoline will also be limited by the blend wall. E85 has the potential to partially alleviate the blending wall constraint, but lack of refueling infrastructure has created limited demand for E85 relative to the flex-fueled fleet and below the supply potential of the ethanol industry. Babcock, Marette, & Treguer (2011) depict the blend wall through an inelastic demand curve for ethanol. Additional reductions in the regulatory limit on ethanol blends, say to 20% as proposed by the corn and ethanol industries, or an increase in U.S. ethanol exports, could increase the elasticity of market ethanol demand (Babcock, Marette, & Treguer, 2011).[47] Within the framework considered in this analysis, the blend wall could be incorporated through a cap on the maximum allowable (or mandated) blend of ethanol in transportation fuel.

Given the model and market assumptions, Figure 3.4 represents the competitive transportation fuel market without cellulosic biofuel mandates. A high cost of cellulosic biofuel production results in zero cellulosic biofuel production in equilibrium and the entire equilibrium quantity of fuel (Q_{NM}) is met by conventional fuels at the market clearing price P_{NM}.

Figure 3.4 – Transportation fuel market without cellulosic biofuel mandate



[47] Findings released in a May 2010 Renewable Fuels Association report (RFA, 2010b) suggest an increase in the ethanol export trend. First quarter 2010 ethanol exports were approximately five times higher than exports in first quarter 2009 and January through March 2010 exports equaled 71% of 2009 total exports.

To incorporate cellulosic biofuel mandates, consider a mandate on the share of total fuel consumption from cellulosic biofuel. The EPA provides annual blending percentage obligation for each type of biofuel computed as "the total amount of renewable fuels mandated to be used in a given year expressed as a percentage of expected total U.S. transportation fuel use" (Schnepf & Yacobucci, 2010, p. 13). In 2012, the revised percentage of fuel required to come from cellulosic biofuel is 0.006%, consistent with 10.45 million gallons. Using the RFS2 cellulosic biofuel mandate of 16 billion gallons in 2022 and the January 2011 Energy Information Agency (EIA) estimates for transportation energy use in 2022, 16 billion gallons of cellulosic ethanol is approximately 7% of 2022 transportation energy use by light-duty vehicles and commercial light vehicles. Let α represent the mandated share of total fuel consumption from cellulosic biofuel. In 2012, $\alpha = 0.00006$ but by 2022 mandate levels (if maintained), α could reach around 0.07.[48]

The blend mandate in the transportation fuel market can be represented by a new supply curve for the mandated blend of cellulosic biofuel and conventional fuel, denoted as $S^M(\alpha)$. This curve will be referred to as the 'mandate fuel supply curve.' The mandate fuel supply curve can be thought of as the price faced by a representative fuel consumer who is mandated to consume fuel in a fixed blend of α parts cellulosic biofuel and 1 - α parts conventional fuel. The price for each unit of mandated fuel mixture (P_M) will equal the weighted price of cellulosic biofuel (P_{CB}) and conventional fuel (P_F) or $P_M = \alpha P_{CB} + (1 - \alpha) P_F$. Figure 3.5 shows the relationship between the cellulosic biofuel, conventional fuel, and mandated blended fuel supply curves for a hypothetical α.

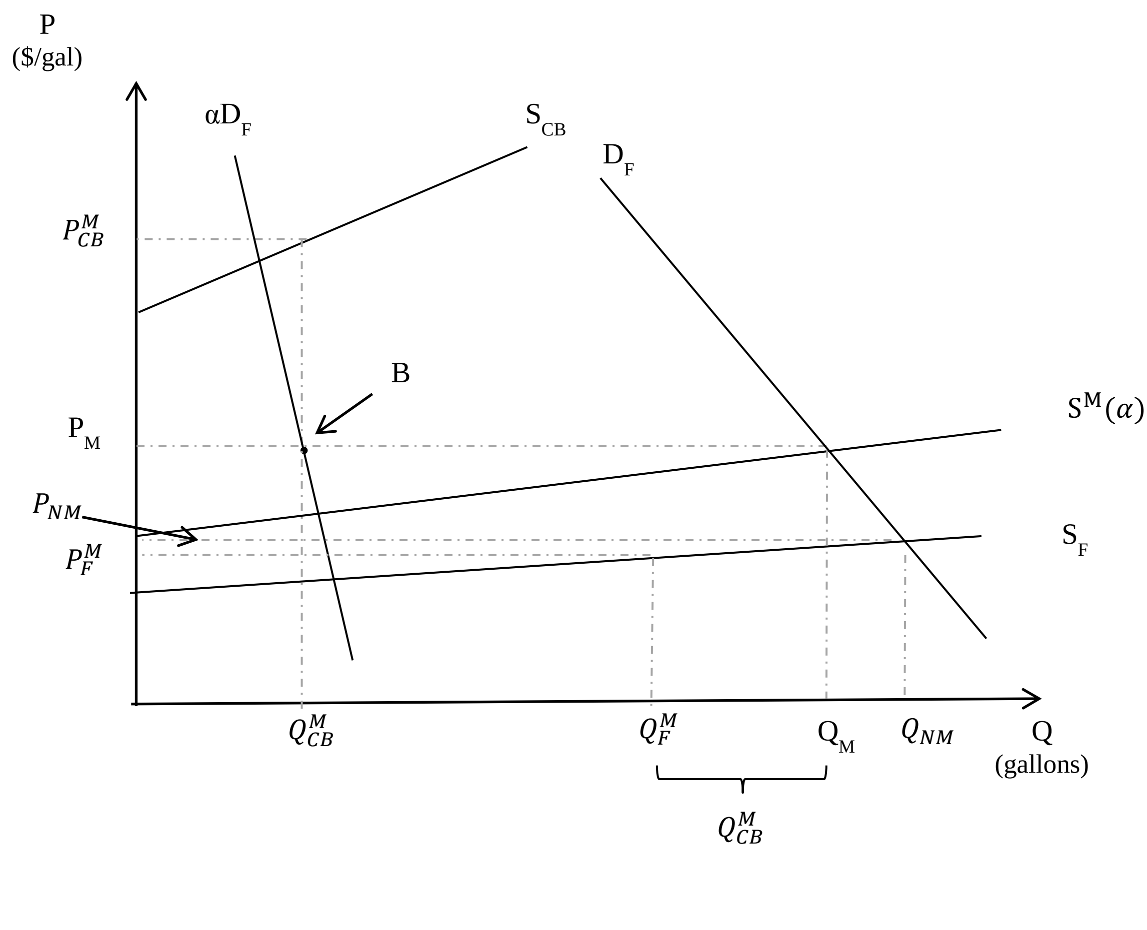
With the mandate fuel supply curve S_M and market demand D_F, the equilibrium price of fuel under the mandate is P_M with conventional fuel price P_F^M and cellulosic biofuel price P_{CB}^M. Since α represents the mandated fraction of total fuel consumption from cellulosic biofuels, the cellulosic biofuel demand curve is αD_F. In Figure 3.5, equilibrium fuel price P_M intersects the cellulosic biofuel

[48] The total renewable fuels mandate in 2022 is 36 billion gallons. At this volume, the blend wall may be reached, limiting the ability to meet the biofuel mandate. In this case, the "blend wall" percentage will act as a cap on the maximum mandated α.

demand curve at point B resulting in Q_{CB}^M gallons of cellulosic biofuel production. The price of cellulosic biofuel (P_{CB}^M) equals the marginal cost of cellulosic biofuel at the equilibrium quantity demanded (Q_{CB}^M).

As shown in Figure 3.5, a blend mandate on cellulosic biofuel when cellulosic biofuel production is otherwise uneconomical increases the equilibrium price of fuel from P_{NM} to P_M and decreases total fuel consumption from Q_{NM} to Q_M.[49] The magnitudes of the price and quantity changes depend on the elasticity of fuel demand with the price impact decreasing and quantity impact increasing as fuel demand becomes more elastic. Demand for fuel in Figure 3.5 is assumed to be relatively inelastic.

Figure 3.5 – Transportation fuel market with cellulosic biofuel mandate (α)



[49] Total fuel consumption will decrease in all but the special case where demand for fuel is perfectly inelastic.

The biofuel mandate shifts a portion of the revenues previously possessed by conventional fuel producers to cellulosic biofuel producers. Consumers also raise per gallon revenues received by fuel producers by paying a higher fuel price. Appendix B.4 provides graphical depictions of the changes in costs and revenues to consumers and producers. In the next section, the model in Figure 3.5 is used to identify the carbon tax needed to induce mandate-level production.

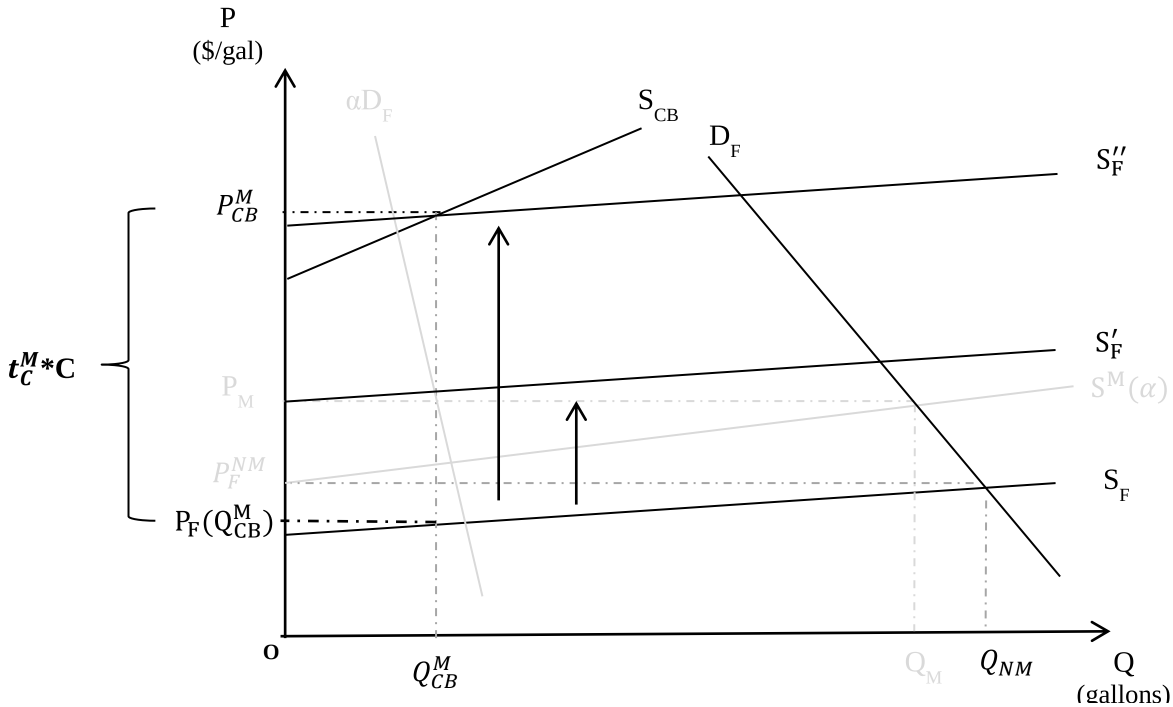
3.5.2 Carbon price for mandate equivalent production

Consider a carbon tax on conventional fuel producers above a baseline GHG emissions level.[50] Assume the baseline level is set at the life cycle GHG emissions from cellulosic biofuel so that conventional fuel producers are taxed for each unit of GHG emissions above cellulosic biofuel. Let t_C denote the carbon tax per unit of emissions and *C* be the emissions rate of conventional fuel above cellulosic biofuel.[51] A carbon tax adds $t_C \times C$ to the cost of conventional fuel production. In Figure 3.6, a carbon tax is equivalent to a vertical shift in the conventional fuel supply curve equal to the tax payment per unit of fuel. The supply curve S_F' represents an insufficient shift to make biofuel competitive without the mandate. With a high enough carbon price or emissions reductions, the carbon tax will shift the supply curve to the point where cellulosic biofuel production will occur without a mandate. The supply curve S_F'' represents the carbon tax needed for cellulosic biofuel production at the mandated production volume (Q_{CB}^M).

[50] Under usual convexity assumptions, a carbon subsidy or payment to cellulosic biofuel producers for each GHG emissions reductions relative to conventional fuel would achieve the same desired result (Weitzman, 1974).

[51] *C* will vary by biofuel feedstock, cellulosic biofuel conversion process, and/or conventional fuel production process. For simplicity, *C* is shown as constant value in the graphical depiction. The variation in *C* is accounted for within the empirical application.

Figure 3.6 – Blend mandate equivalent carbon tax or credit



The carbon emissions per gallon above cellulosic biofuel emissions (C), marginal cost of cellulosic biofuel (P_{CB}^{M}), and price of transportation fuel at the mandated biofuel volume $[P_F(Q_{CB}^{M})]$ can be used to calculate the carbon tax (t_C^M) that would induce cellulosic biofuel production equal to the mandate volume if carbon taxes were used in lieu of mandates, or

$$t_C^M = \frac{P_{CB}^M - P_F(Q_{CB}^M)}{C}. \qquad \textbf{(5)}$$

The price derived in equation (5) can be interpreted as the value of emissions reductions implied by the cost to meet the cellulosic biofuel mandate. This calculation attributes the full cost of sustaining cellulosic ethanol production to GHG emissions reductions and does not consider other potential motivations for biofuel production, such as energy security, rural development, or trade balance. Therefore, this carbon valuation can be viewed as an upper limit on the valuation of carbon emissions reductions implied by the RFS2 mandate since any cost attributed to other motivations will reduce the price gap closed by the carbon tax.

3.5.3 Mandate equivalent implicit carbon tax/credit from BioBreak program results

Results from BioBreak are used in conjunction with GHG emissions reductions to identify the carbon tax or price needed to sustain local cellulosic ethanol markets in the long-run. Per gallon price gap estimates from the BioBreak program provide estimates of $(P_{CB} - P_F)$ under varying economic and policy conditions. Estimates of GHG emissions reductions are taken from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (GREET 1.8d), an Excel-based program developed by the Center for Transportation Research at Argonne National Laboratory. GREET provides life-cycle GHG emissions for both conventional gasoline and feedstock-specific cellulosic biofuel (Wang, 2007). To provide a consistent analysis, default assumptions in GREET were adjusted to fit the feedstock, location, and technology assumptions used in the BioBreak application.[52] The life-cycle GHG emissions reduction from replacing a unit of conventional fuel with cellulosic ethanol ranges between 64% and 77%.[53] In terms of biomass feedstock, emissions are reduced between 0.40 and 0.49 metric ton of CO_2 equivalents (mt CO_2e) per ton of biomass used for cellulosic ethanol. These estimates provide a measure of the GHG emissions from conventional gasoline above cellulosic ethanol (C). For a baseline carbon price scenario, we use baseline BioBreak assumptions including $100 per barrel oil, 70 gallons ethanol per dry ton feedstock, and no policy incentives. Further, the biorefinery is assumed to operate with 2010 technology for the GREET program. Since the timing of cellulosic ethanol market development is indeterminate, sensitivity of model results to biorefinery technology and ethanol fuel economy assumptions will be considered.

In the baseline scenario, the carbon price implied by the cost needed to sustain local cellulosic ethanol markets ranges between $141 and $280 per mt CO_2e. Table 3.7 provides estimates

[52] One shortcoming of GREET 1.8d is the inability to adjust biomass yield assumptions. GHG emissions per mile used in this analysis were calculated using the GREET baseline yield assumptions for each feedstock.
[53] The baseline scenario assumes 23.12 miles per gallon (mpg) fuel economy for 2010, equivalent to the 2010 default value for E85 and conventional fuel vehicles in GREET. The average fuel economy for all passenger cars (used and new) was 22.6 mpg in 2008. In 2009, the CAFE standard was 27.5 mpg, but the average estimated fuel economy for new passenger cars was 32.6 mpg (BTS - RITA, 2010).

for the implicit carbon prices needed to sustain local cellulosic ethanol production under alternative oil price and technology assumptions. Any change in BioBreak model assumptions that increase the economic feasibility of cellulosic ethanol will decrease the carbon price needed to sustain markets. Similarly, any change in GREET model assumptions that increases emissions reductions from cellulosic ethanol relative to conventional gasoline will decrease the per unit carbon tax needed to sustain markets. If conditions are such that cellulosic ethanol is feasible without a carbon tax, the mandate is non-binding and the level of cellulosic ethanol production will be determined by the competitive market conditions.

Table 3.7 – Implicit carbon price needed to sustain a biomass market for a 53.4 mgy biorefinery (\$/mt CO_2e)

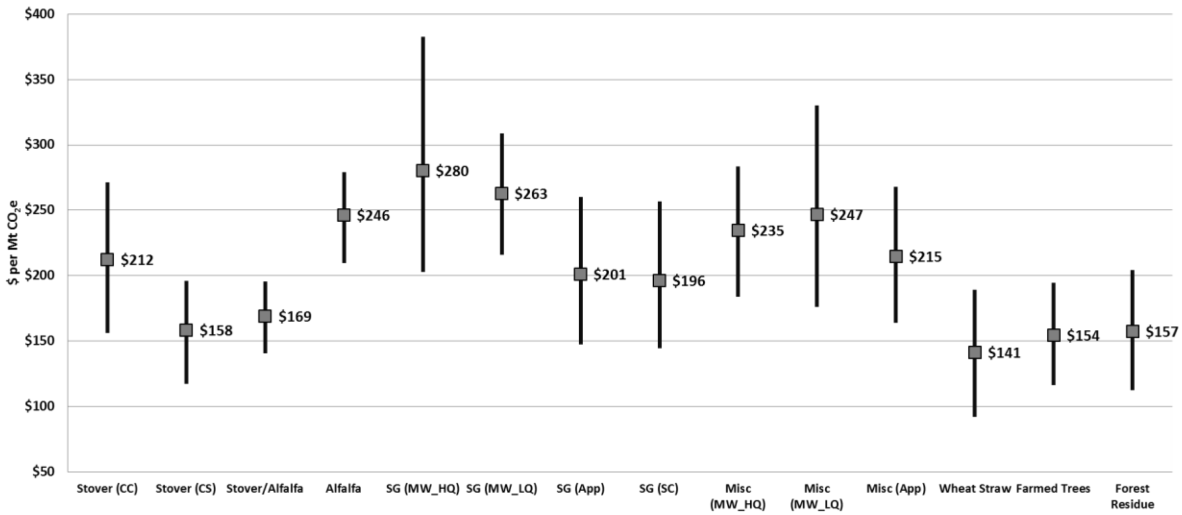
(Baseline assumptions unless noted otherwise, 2007$)

	$100 oil	**$50 oil**	**$150 oil**	**80 gal/ton & 2020 biorefinery**	**Tax credit**
Stover (CC)	$211	$379	$44	$165	$65
Stover (CS)	$157	$325	$0	$119	$11
Stover/Alfalfa	$169	$349	$0	$125	$10
Alfalfa	$246	$444	$48	$187	$73
Switchgrass (MW HQ)	$280	$475	$84	$216	$109
Switchgrass (MW LQ)	$264	$459	$69	$203	$91
Switchgrass (App)	$201	$396	$7	$150	$30
Switchgrass (SC)	$195	$390	$0	$145	$25
***Miscanthus* (MW HQ)**	$236	$431	$42	$180	$64
***Miscanthus* (MW LQ)**	$247	$442	$53	$189	$76
***Miscanthus* (App)**	$214	$409	$20	$161	$44
Wheat straw	$141	$338	$0	$99	$0
Farmed trees	$154	$319	$0	$117	$10
Forest residues	$158	$359	$0	$109	$0

Note: Carbon price estimates censored below at $0. Life cycle emissions for ethanol based on E85 flex-fuel vehicle and 2010 biorefinery unless noted otherwise.

At a long-run oil price of \$50 per barrel, the implicit carbon price increases to range between \$319 and \$475 per mt CO_2e (Table 3.7, Column 2). With \$150 per barrel oil, several local cellulosic ethanol markets will be sustainable without carbon pricing, and for the other cellulosic ethanol markets, carbon prices range between \$7 and \$84 per mt CO_2e (Table 3.7, Column 3). Finally, with a conversion ratio of 80 gallons per ton and 2020 GREET biorefinery technology, the implicit carbon price decreases to range between \$99 and \$216 per mt CO_2e (Table 3.7, Column 4). Based on the stochastic output from BioBreak, Figure 3.7 provides the 90% confidence interval for the implicit carbon price in the baseline scenario. Although not shown here, availability of waiver credits would place a cap on the implicit price of carbon.

Figure 3.7. The 90% confidence interval for the implicit carbon price needed to sustain a biomass market for a 53.4 mgy biorefinery (\$/mt CO_2e)
(Baseline assumptions, 2007$)



3.5.4 Comparison of carbon price estimates with previous literature

The upper range of the baseline carbon price estimates are consistent with a July 2010 Congressional Budget Office (CBO) report which estimated a cost of $275 per metric ton to reduce GHG emissions through the cellulosic biofuel tax credit. Beyond the CBO report, the baseline carbon price estimates (\$141 - \$280 per mt of CO_2e) are higher than most carbon prices assumed or estimated in previous literature. Brechbill & Tyner (2008b) estimate the price of carbon implied by the cost to replace 10% of total heat product in a coal power plant at $5.80 - $10 for corn stover and $14.50 - $15.20 for switchgrass. Schneider & McCarl (2003) evaluate the economic potential of biofuels in the GHG mitigation market and find biofuels are not competitive at a carbon price below $40 per ton but dominate all other agriculture mitigation strategies above $70 per ton. In a meta-analysis of 211 estimates of the social cost of carbon, Tol (2008) found a modal value of $35, median value of $74, and average value of $127 per metric ton. Higher estimates were predominately from gray literature. Other studies assume carbon prices between $0 and $160 when analyzing impacts of carbon markets or pricing, with sensitivity up to $500 per ton (Table 3.8).

Table 3.8 – Carbon price estimates or assumptions within the literature

Source	Carbon price(s)
Baker et al. (2010)	$0-$50
Beresteanu & Li (2011)	$177
Brechbill &Tyner (2008b)	$5.80-$10 (stover) $14.50-15.20 (switchgrass)
de la Torre Ugarte et al. (2009)	Up to $160
de la Torre Ugarte et al. (2009)	$80
EPA (2006)	$0-$60
EPA cited by Golub et al. (2008)	$50 ($1-$100)
Gomes & Araujo (2009)	$20, $50, $100
Johnson (2006)	$63
Khanna (2008)	$34
McCarl & Schneider (2001)	$0, $10, $50, $100, $500
Murray et al (2005)	$1, $5, $15, $30, $50
Parry & Small (2005)	$25 ($0.70 - $100)
Schneider & McCarl (2003)	$0-$500 (range analyzed) < $40 (no role for biomass) >$70 (biofuels dominate)
Tol (2008)	$35 (mode) $74 (median) $127 (average)
Updegraff, Baughman, & Taff (2004)	$7 ($1.22 - $44)

Compared to other policy programs implemented to reduce carbon emissions, cellulosic ethanol production has similar costs per unit of emissions savings. Since 2000, the U.S. government has supported hybrid vehicle consumption through federal income tax deductions (before 2006) and federal income tax credits (since 2006). Beresteanu & Li (2011) estimated the cost of CO_2 emissions reduction through the hybrid vehicle federal income tax credit program at around $177 per ton in 2006. In the summer of 2009, subsidies were granted to car owners who traded in old, fuel inefficient vehicles to purchase new and more efficient vehicles, commonly referred to as the 'Cash-for-Clunkers' program. Li, Linn, & Spiller (2011) estimated the Cash-for-Clunkers program reduced CO_2 emissions at a cost of $91 to $288 per ton.

3.6 Conclusions

The RFS2 requires cellulosic biofuel be part of the liquid transportation fuel mix, with a minimum annual use of 16 billion gallons of cellulosic biofuel by 2022. Available knowledge regarding costs of producing cellulosic biomass and converting it to cellulosic biofuel is largely based on engineering estimates and experimental trials. At the same time, previous literature has overlooked market conditions required for the development of second-generation biofuel markets (Babcock, Marette, & Treguer, 2011). The BioBreak program was developed to evaluate the economic feasibility of local cellulosic ethanol markets under different economic and policy environments. For uneconomical markets, BioBreak provides estimates of the price gap that needs to be closed to sustain local markets and meet mandated production levels.

An application to 14 potential markets found cellulosic ethanol markets are not likely to achieve long-run breakeven without significant government intervention or higher long-run oil prices. The gap between the supply price and derived demand price ranges from $57 to $115 per ton of feedstock, or equivalently, $0.82 to $1.65 per gallon cellulosic ethanol. Additional policy incentives or high long-run oil prices significantly reduce price gaps and result in economical long-run biofuel production. The economic costs of biofuel production identified from the BioBreak application are higher than frequently anticipated[54] and raise questions about the potential of cellulosic ethanol as a sustainable and economical substitute for conventional fuels.

If we interpret the price gap in the absence of government incentives as reflecting the cost of carbon savings associated with each gallon of cellulosic ethanol, we can derive the implicit price per unit of carbon equivalent savings from mandating cellulosic biofuel production. This approach would imply a carbon equivalent cost between $141 and $280 per metric ton, higher than most carbon prices

[54]A subset of the literature that falls within this category includes: Aden (2008), Aden et al. (2002), Brechbill & Tyner (2008a), Brechbill & Tyner (2008b), de La Torre Ugarte et al. (2003),Epplin & Haque (2011), Epplin et al. (2007), Graham et al. (2007), Huang et al. (2009), Khanna & Dhungana (2007), Mapemba et al. (2007), Mapemba et al. (2008), McLaughlin et al. (2002), McLaughlin et al. (2006), Perlack & Turhollow (2002), Perlack & Turhollow (2003), Petrolia (2008), Popp & Hogan (2007), Sheehan et al. (2004), Vadas et al. (2008), and Wallace et al. (2005).

discussed in the literature, but within the range of costs from other U.S. policies implemented to reduce GHG emissions.

CHAPTER 4. CELLULOSIC BIOFUEL SUPPLY WITH HETEROGENOUS BIOMASS SUPPLIERS: AN APPLICATION TO SWITCHGRASS-BASED ETHANOL

A modified version of the chapter to be submitted to a peer-reviewed journal

Abstract

The potential of biomass for alternative energy production has attracted considerable attention because of associated implications for energy security, food supply, and climate change. This chapter considers the economic impacts of spatial variation and landowner behavior on potential biomass supply for U.S. cellulosic biofuel. To examine these impacts, we develop and apply a long-run biomass production through bioenergy conversion cost model that incorporates heterogeneity of biomass suppliers within and between local markets. In an application to U.S. switchgrass-based cellulosic ethanol production, we find cost-minimizing biofuel production decisions, which include biorefinery size, biomass transportation distance, and price of biomass, vary significantly across locations. We develop an aggregate switchgrass ethanol supply curve from the cost-minimizing local biorefinery capacities and production costs to evaluate the potential for and cost of achieving cellulosic biofuel production targets such as the revised Renewable Fuels Standard (RFS2) mandates. Switchgrass-based ethanol could satisfy the 2016 RFS2 cellulosic biofuel mandate of 4.25 billion gallons per year at a cost of $3.52 per gallon ethanol ($5.30 per gallon gasoline equivalent). By accounting for observed heterogeneity in potential biomass suppliers within and between local markets, we trade-off economies in biomass production, transportation, and conversion not previously obtained. Empirical results suggest spatial variation in the economics of biomass production plays an important role in the potential supply and distribution of U.S. cellulosic biofuel production.

4.1 Introduction

Unstable energy prices and concern about the environmental impacts of growing greenhouse-gas (GHG) emissions have increased interest in finding alternative sources of energy. The use of biomass, a renewable and potentially GHG-reducing energy source, has gained significant attention and political support in the United States. In addition to allocating federal funds to bioenergy research projects, the United States has imposed mandates and provided market incentives to stimulate bioenergy production and consumption. The revised U.S. Renewable Fuel Standard (RFS2) took effect July 2010 and mandates a minimum contribution from cellulosic biofuel – the form of bioenergy considered in this chapter – to the U.S. transportation fuel mix through 2022. Several biomass-to-biofuel conversion methods exist, but the economics of cellulosic biofuel production has limited industry development. The first commercial scale cellulosic biorefinery isn't expected to be operational until 2013.[55]

The amount of biomass that must be supplied for commercial scale production presents a significant challenge to industry development. A national biomass market does not exist and is unlikely to develop given the high costs of biomass transportation (Babcock, Marette, & Treguer, 2011).[56] As a result, cellulosic biorefineries will rely on local biomass markets for feedstock supply. The quantity and price at which potential biomass suppliers are willing and able to supply biomass to a biorefinery will vary both between and within local markets. Between markets, the amount of sustainable biomass production varies due to geographical and climate differences. Within local markets, potential suppliers differ in their perceived costs and benefits of biomass production even with relatively uniform production conditions (Bergtold, Fewell, & Williams, 2011; Tyndall, 2007; Tyndall, Berg, & Colletti, 2011; Hipple & Duffy, 2002; Wen, Ignosh, Parrish, Stowe, & Jones, 2009; Altman, Bergtold, Sanders, & Johnson, 2011).

This chapter evaluates the economic trade-offs faced by commercial-scale cellulosic biofuel production that result from spatial variation and landowner heterogeneity in potential biomass supply. We begin with a theoretical long-run cost model, or supply model, from biomass production through bioenergy conversion that incorporates biomass supplier heterogeneity within and between local markets. A primary contribution of this chapter is the treatment of local biomass supply within the

[55] The 25 million gallon cellulosic ethanol plant proposed by POET for Emmetsburg, Iowa is expected to be the first commercial scale cellulosic biorefinery. The Emmetsburg biorefinery was originally scheduled to be completed and operational by 2011 but faced several setbacks, including a delay in the government loan. Only pilot-scale plants are in operation.

[56] Babcock, Marette, & Treguer (2011, p. 717) note one potential exception is the development of a "spatially integrated market for treated feedstocks" if a pretreatment technique for feedstocks is created to significantly increase feedstock value and density. A recent effort to develop a commoditized feedstock market for biomass is the Biomass Commodity Exchange (BCEX), http://www.biomasscommodityexchange.com/.

theoretical model of cellulosic biofuel production cost. While previous literature has assumed the fraction of local landowners willing and able to participate in biomass supply is fixed and independent of the price of biomass, we incorporate a functional relationship between the rate of landowner participation and the price of biomass. We hypothesize that accounting for these location-specific functional relationships will result in significant variation in the cost-minimizing production decisions across locations which, ultimately, have important impacts on the potential supply, distribution, and economics of cellulosic biofuel. To test this hypothesis, the theoretical model is applied to switchgrass-based ethanol production in the United States using biofuel processing costs, switchgrass production costs, and offers submitted nationally for enrollment in the Conservation Reserve Program (CRP). The CRP offers data, which provides revealed information on landowner's willingness to forgo current agricultural production in exchange for an annual fixed payment, is used to identify heterogeneity in the opportunity cost of potential dedicated biomass cropland within each region that, to our knowledge, has not been done before. Data are incorporated into a non-linear mathematical programming model to determine the cost-minimizing production decisions – including biorefinery size, capture region distance, feedstock price, and average cost of cellulosic ethanol production – for each potential biorefinery location. The estimated local ethanol supplies are combined to generate an aggregate ethanol supply curve. The resulting supply curve is used to evaluate the economic trade-offs that exist as a result of spatial variation and landowner heterogeneity as well as the potential for and costs to meet the RFS2 cellulosic biofuel mandates.

The chapter is organized as follows. The next section discusses the economic trade-offs in cellulosic biofuel production that differentiates it from petroleum-based transportation fuel and first-generation biofuel production (e.g., corn ethanol, soybean biodiesel). Section 4.3 presents the theoretical model for cellulosic biofuel production cost with heterogeneous biomass suppliers. Section 4.4 describes the empirical specification and data used in the application of the theoretical model to U.S. switchgrass-based ethanol production. Results, including sensitivity analysis, are presented in Section 4.5. Section 4.6 concludes with a discussion of model implications, policy relevance, and future extensions in this area of research.

4.2 Cost structure for cellulosic biofuel production

The cellulosic biofuel industry has a different cost structure than petroleum-based transportation fuel or first-generation biofuel. Petroleum-based industries realize economies in scale in processing but do not have or realize any scale economies in feedstock procurement (i.e., average feedstock costs are independent of plant size). Processing economies, up to a point, lead to large-scale petroleum-based refineries (Wright & Brown, 2007; Searcy & Flynn, 2009).[57] By operating within local feedstock markets, biofuel producers face a trade-off between economies of scale in biofuel processing and diseconomies of scale in feedstock procurement. First-generation biorefineries use commoditized feedstocks with a market price (e.g., corn, soybeans). The increase in feedstock demand from a larger capacity first generation biorefinery is met by paying the market price for additional feedstock located farther from the biorefinery and paying a greater transportation cost. The trade-off between economies of scale in processing and diseconomies of transportation results in a cost-minimizing combination of feedstock transportation distance and biorefinery capacity. This cost-minimizing combination is independent of the market price of feedstock (Searcy & Flynn, 2009).[58] As explained in more detail in the next paragraph, this modeling framework is not representative of the cellulosic biofuel industry. Therefore, the model we develop for cellulosic biofuel production will relax the independence assumption and allow the cost-minimizing decisions to depend on the price of feedstock.

Cellulosic biorefineries use a non-commoditized feedstock, making their economic trade-offs more complex. The biorefinery's cost-minimizing decisions depend on the offered price of biomass.

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[57] In this chapter we do not differentiate between economies of scale and economies of size and use the term "economies of scale" to represent decreasing per unit cost of production with capacity. See Hallam (1991) for definitions and a discussion of the differences between and measures of economies of scale and size.
[58] This relationship will be shown in detail in Section 4.3.4.

The fraction of land allocated into biomass production will be determined by the fraction of land for which the offered price of biomass covers all costs incurred from biomass production, including opportunity costs. We refer to this fraction as the “participation rate” for biomass supply. The relationship between the participation rate and price of biomass adds complexity to the cost structure of biomass procurement.

To illustrate the economic trade-offs involved in biomass procurement, a simplified example is outlined in Figure 4.1. Consider a potential biorefinery that plans to offer biomass suppliers a price P_0 per ton of biomass, and suppose the participation rate within the local market is d_0 at the biomass price P_0. Given d_0, let r_0 denote the radius of the circular capture region needed to satisfy feedstock demand if the biorefinery builds a biorefinery with capacity Q_0 gallons per year (Figure 4.1a). Now suppose the biorefinery recognizes there are economies of scale in biofuel processing and considers building a different capacity, Q_1, where $Q_1 > Q_0$. The increase in feedstock demand from the larger capacity cellulosic biorefinery can be met in one of three ways. First, the biorefinery can maintain the offered price of biomass P_0 and the participation rate d_0 and satisfy the increase in feedstock demand by contracting additional feedstock located farther from the biorefinery. The larger capture region is depicted in Figure 4.1b by radius $r_2 > r_0$.[59] Second, the biorefinery can maintain the size of the capture region (r_0) but increase the participation rate within the local market to $d_2 > d_0$ through an increase in the price offered for feedstock to $P_2 > P_0$. Third, the biorefinery could use a combination of both. Although a continuum of combinations are feasible, Figure 4.1b illustrates one possible combination with radius r_1 (where $r_0 < r_1 < r_2$), price of biomass P_1 (where $P_0 < P_1 < P_2$), and participation rate d_1 (where $d_0 < d_1 < d_2$). Any of the three methods to satisfy feedstock demand for a larger biorefinery increases average feedstock cost, resulting in diseconomies of feedstock procurement. This economic trade-off between economies of scale in cellulosic biofuel processing and diseconomies of scale in

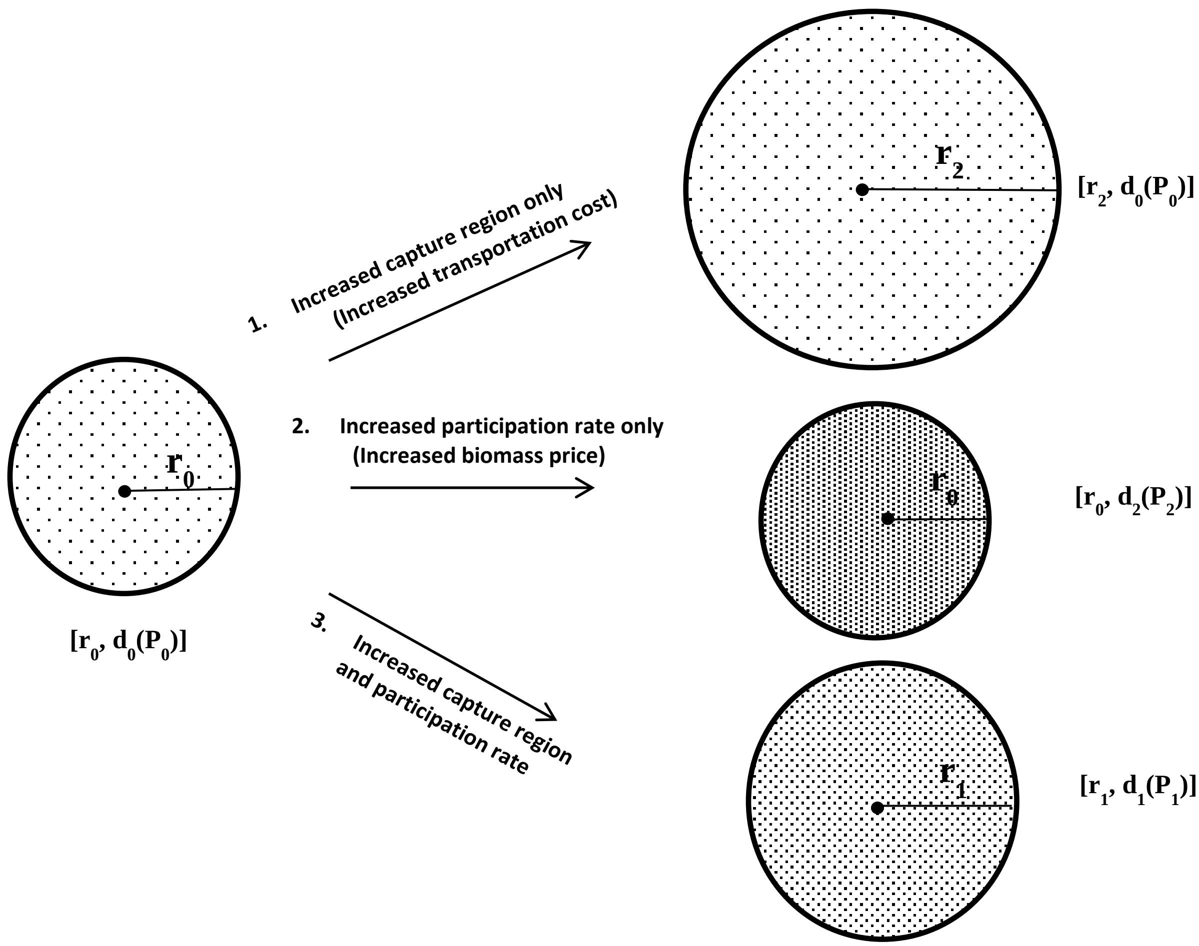
[59] An implicit assumption here is that potential biomass suppliers farther from the biorefinery have the same supply responsiveness or willingness to participate as potential biomass suppliers located close to the biorefinery.

feedstock procurement leads to cost-minimizing biofuel production decisions that are location dependent and include biorefinery size, biomass transportation distance, and also the price of feedstock.

Figure 4.1 – Three possible participation rate and capture region combinations that satisfy an increase in feedstock demand associated with an increase in biorefinery capacity

a. Capture region radius (r_0) to meet feedstock demand for a biorefinery with capacity Q_0 given a participation rate d_0 at the offered feedstock price of P_0.

b. Three possible participation rate and capture region combinations to meet feedstock demand for a biorefinery with capacity $Q_1 > Q_0$.



Note: $r_0 < r_1 < r_2$, $d_0 < d_1 < d_2$, $P_0 < P_1 < P_2$

The theoretical model presented in the next section incorporates these economic trade-offs into a cellulosic biofuel long-run production cost model. To our knowledge, this is the first analysis to explicitly incorporate this relationship into a production cost model for cellulosic biofuel; however, previous literature has recognized the existence and importance of this relationship. Leboreiro & Hilaly (2011, p. 2713) note landowner participation rate in biomass supply is "a strong function of the economic incentive," but proceed in the convention of previous literature[60] by assuming fixed values for the participation rate and economic incentive (i.e., supplier payment) and then conducting independent sensitivity analysis to changes in the fixed values.

4.3 Theoretical framework: long-run cellulosic biofuel production cost

The theoretical framework presented here builds on a growing body of literature that considers the production capacity choice of a potential biorefinery prior to capital investment.[61] The biorefinery is assumed to minimize the long-run total cost per unit of biofuel production (C) by choosing the production capacity and price of biomass to offer to local biomass suppliers, conditional on the biorefinery technology and local biomass supply conditions.[62] A biorefinery's total production cost is a function of its feedstock procurement costs (C_F) and biofuel processing costs (C_P).

4.3.1 Feedstock procurement cost

The per ton cost of feedstock procurement includes the price paid to local biomass suppliers (P_F), storage cost (S), and transportation cost. The transportation cost per ton of feedstock is derived

[60] See Cameron, Kumar, & Flynn (2007b), Dornburg & Faaij (2001), Gan (2007), Gan & Smith (2010), Huang, Ramaswamy, Al-Dajani, Tschirner, & Cairncross (2009), Jenkins (1997), Kaylen, Van Dyne, Choi, & Blasé (2000), Kaylen, Van Dyne, Kumar, Cameron, & Flynn (2003), Nguyen & Prince (1996), Searcy & Flynn (2009), Searcy & Flynn (2010), and Wright & Brown (2007b).
[61] A subset of the literature which examines biorefinery minimum efficient capacity includes: Cameron, Kumar, Cameron, Kumar, & Flynn (2007b), Dornburg & Faaij (2001), Gan (2007), Gan & Smith (2010), Jenkins (1997), Leboreiro & Hilaly (2011), Nguyen & Prince (1996), Searcy & Flynn (2009), and Wright & Brown (2007b).
[62] Assuming cellulosic biofuel and conventional fuel are perfect substitutes in consumption on an energy equivalence basis and fuel markets are competitive, minimizing long-run average total cost (that is, the point where the long-run average total cost equals the marginal cost) yields the same solution as profit maximization.

by multiplying the per mile per ton transportation cost (t) by the capture radius (r).[63] Equation (1) calculates the per gallon cost of feedstock procurement (C_F) by dividing total per ton feedstock costs by the gallons of biofuel produced from each ton of feedstock, commonly referred to as the biofuel yield (Y_O).

$$C_F(Q, P_F) = \frac{1}{Y_O} \times [P_F + S + t \times r(Q, P_F)]. \tag{1}$$

The capture radius for a biorefinery operating with a capacity of Q gallons per year is derived from the methodology in French (1960) for a circular capture area with uniform biomass density:

$$r = \gamma \times \sqrt{\frac{Q}{Y_O \times Y_B \times d}} \tag{2}$$

where Y_B is the biomass yield per acre, d is the fraction, or density, of land allocated to biomass production within the region, and γ is a conversion factor.[64]

Holding all other variables constant, an increase in biorefinery capacity will increase the capture radius and per unit cost of feedstock transportation $\left(\frac{\partial r}{\partial Q} > 0\right)$. Conversely, an increase in the fraction of land allocated to biomass production will decrease the capture radius and per unit cost of feedstock transportation holding all other variables constant $\left(\frac{\partial r}{\partial d} < 0\right)$. Therefore, depending on the local biomass supply conditions, an increase in the fraction of land allocated to biomass supply could partially or fully offset the need to increase transportation distance to meet feedstock demand for a

[63] Capture radius is used as opposed to the average hauling distance to account for location or bid rents. In the long-run and assuming the biorefinery does not have monopsony power to price discriminate, biomass suppliers located closer to the biorefinery will receive location or bid rents regardless of which party is responsible for transportation. If biomass suppliers handle transportation and the biorefinery pays each supplier a fixed transportation payment per ton of biomass equal to the product of the variable transportation cost (t) and capture region radius (r), a biomass supplier located x miles from the biorefinery will receive location-specific benefits equal to $t * (r - x)$ per ton. If the biorefinery handles transportation, the biomass supplier will receive an equivalent bid-rent value [i.e., $t * (r - x)$ per ton] by requiring a higher opportunity cost payment to supply biomass. The model presented here mirrors the grain industry and captures bid rents through the use of the capture radius to calculate the transportation cost for each unit of biomass. Sensitivity analysis will consider the potential for a biorefinery to price discriminate and capture transportation-related rents.

[64] With the capture radius measured in miles and biomass yield measured per acre, γ for a circular area is 0.0223. The value for γ will differ based on the transportation structure assumed (e.g., average hauling distance vs. capture radius, circular vs. square supply plane, road grid, etc.).

larger biorefinery. Landowners respond to price incentives and the fraction of land allocated to biomass production will be non-decreasing in the price of biomass. This relationship is captured in the procurement cost model through a location-specific function $d(P_F)$, where $\frac{\partial d(P_F)}{\partial P_F} \geq 0$. We refer to $d(P_F)$ as the local participation rate function.[65]

Incorporating equation (2) and the local participation rate function into equation (1) produces the following equation for the per gallon cost of feedstock procurement (C_F):

$$C_F(Q, P_F) = \frac{1}{Y_O} \times \left[P_F + S + t \times \gamma \times \sqrt{\frac{Q}{Y_O \times Y_B \times d(P_F)}}\right]. \quad (3)$$

4.3.2 Biofuel processing cost

Biofuel processing costs arise in converting biomass into cellulosic biofuel and depend on the biorefinery technology and capacity. There are per-gallon costs that depend on biorefinery capacity and exhibit economies of scale ($C_{P,Q}$) and there are per-gallon costs that are independent of biorefinery capacity ($C_{P,N}$). A power function is used to model biorefinery costs that exhibit economies of scale (Brown, 2003) and assumes the following relationship between the per-gallon cost at capacity Q_0 and per-gallon cost at capacity Q_1:

$$Cost_{Q_1} = Cost_{Q_0} \times \left[\frac{Q_1}{Q_0}\right]^{k-1}. \quad (4)$$

The scaling factor, $k \geq 0$, represents the rate at which total cost increases with capacity, or equivalently, $k - 1$ represents the rate at which per-gallon cost changes with capacity.[66] With economies of scale, k is strictly less than one. For a biorefinery with capacity Q, the power function for processing costs that exhibit economies of scale can be written as follows:

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[65] Including the relationship between participation in feedstock supply and the price of biomass allows the biorefinery the flexibility to meet an increase in feedstock demand (increased Q) at least cost through transporting biomass from farther locations, increasing the biomass density (increased P_F), or a combination of the two.

[66] A more common, but equivalent, representation of the power function is: $\text{Total Cost}_{Q_1} = \text{Total Cost}_{Q_0} \times \left[\frac{Q_1}{Q_0}\right]^{k}$.

$$C_{P,Q} = C_{P,Q_0} \times \left[\frac{Q}{Q_0}\right]^{k-1}, \tag{5}$$

where C_{P,Q_0} and k are exogenous, known variables and C_{P,Q_0} represents per-gallon costs for a "baseline" biorefinery with capacity Q_0. Assuming the biorefinery operates at annual capacity through the life of the plant, equation (5) and the biofuel processing costs independent of biorefinery capacity together imply the following expression for the per-gallon total cost of processing biofuels (C_P):

$$C_P(Q) = C_{P,N} + C_{P,Q_0} \times \left[\frac{Q}{Q_0}\right]^{k-1}. \tag{6}$$

4.3.3 Biorefinery objective function

Combining equations (3) and (6), the objective function for the cost-minimizing biorefinery can be written as follows:

$$\min_{Q,P_F} \; C(Q,P_F) = \min_{Q,P_F} \; C_{P,N} + C_{P,Q_0} \times \left[\frac{Q}{Q_0}\right]^{k-1} + \frac{1}{Y_O} \times \left[P_F + S + t \times \gamma \times \sqrt{\frac{Q}{Y_O \times Y_B \times d(P_F)}}\right] \tag{7}$$

where
$$\frac{\partial d(P_F)}{\partial P_F} \geq 0$$
$$d(P_F) \in [0,1]$$
$$Q, P_F \geq 0.$$

The trade-off between economies of scale in biofuel processing and diseconomies of feedstock procurement results in a cost function that is convex in Q and P_F.[67] The first order conditions with respect to capacity and price of feedstock lead to the following equation[68]:

$$Q^* = \left[\frac{\partial d(P_F^*)}{\partial P_F} \times \frac{4 \times C_{P,Q_0}^3 \times (1-k)^3 \times Y_O^4 \times Y_B}{t^2 \times \gamma^2 \times Q_0^{3(k-1)}}\right]^{\frac{1}{4-3k}}. \tag{8}$$

Equation (8) requires specification of the participation rate function, $d(P_F)$, and can be solved using a non-linear mathematical programming model.

[67] The necessary and sufficient conditions for convexity are provided in Appendix C.1 and satisfied during estimation.
[68] Derivation of equation (8) is provided in Appendix C.2.

4.3.4 Fixed biomass density approach: use and limitations

The biorefinery's problem has been simplified in previous literature by assuming the fraction of land allocated to biomass production and the price of biomass are fixed and independent of plant size. This approach assumes increased feedstock demand can only be met by traveling farther to acquire additional biomass, leading to a cost-minimizing capacity (equation 9) and capture radius (equation 10) that depend on an assumed fixed density value (d_{fixed}) but are independent of the price of biomass ($P_{F,fixed}$).[69]

$$Q^*_{fixed\ d} = \left[\frac{2 \times C_{P,Q_0} \times (1-k) \times \sqrt{Y_O^3 \times Y_B \times d_{fixed}}}{t \times \gamma \times Q_0^{k-1}}\right]^{\frac{2}{3-2k}}. \quad (9)$$

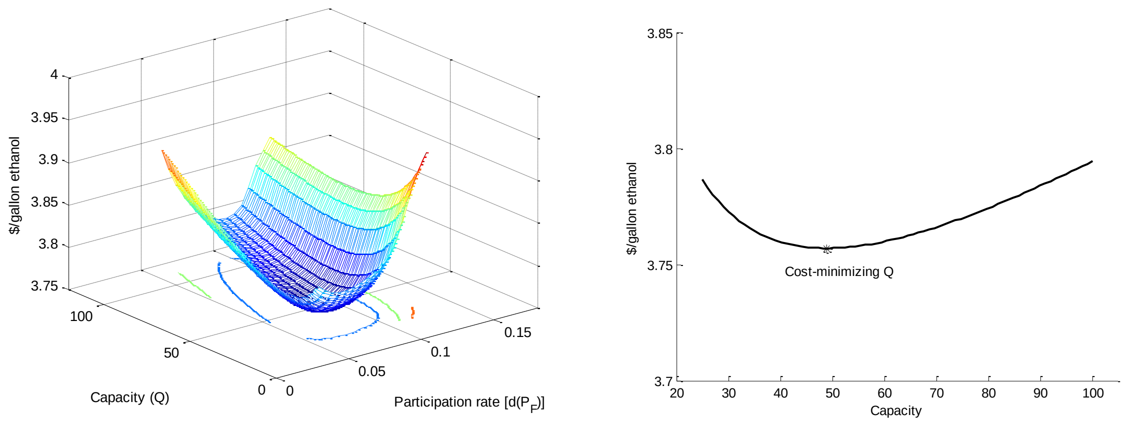
$$r^*_{fixed\ d} = \gamma \sqrt{\frac{Q^*_{fixed\ d}}{Y_O \times Y_B \times d_{fixed}}}. \quad (10)$$

With an endogenous participation rate $[d(P_F)]$, the biorefinery's long-run cost can be depicted as a surface graph plotted over a range of capacities and local participation rates (Figure 4.2a). The solution to the biorefinery objective function is the capacity and local participation rate with corresponding price of biomass at the minimum of the cost surface. A fixed participation rate approach used in previous literature is equivalent to selecting and evaluating a 'slice' from the biorefinery cost surface at a fixed participation rate (Figure 4.2b). The biorefinery objective function is simplified to a single variable problem for the minimum efficient capacity (Q). Unless the fixed participation rate and price of biomass are set exactly at the cost-minimizing values from the cost surface, the estimated minimum cost of biofuel production and minimum efficient capacity will differ between an endogenous and fixed value analysis.

[69] Appendix C.3 provides the derivation of equations (9) and (10) along with a summary of the marginal impacts of model parameters on cost-minimizing biorefinery capacity and biomass hauling distance.

Figure 4.2 – Biorefinery cost function for a select location

(a). Endogenous participation rate (b). Fixed participation rate[70]



The assumptions of a fixed biomass density and price provide a useful analytical simplification but at the sacrifice of an important economic relationship – potential biomass suppliers will respond to price incentives. Acreage supplied into biomass production should increase with the price of biomass. Recent survey results suggest that potential biomass suppliers respond as expected – the quantity of acreage willing to be allocated into biomass production increases with the price of biomass offered (Altman, Bergtold, Sanders, & Johnson, 2011; Menard, Jensen, Qualls, English, & Clark, 2011; Qualls, Jensen, English, Larson, & Clark, 2011). Landowners were also found be heterogeneous in their willingness to supply biomass even under relatively uniform production conditions (Bergtold, Fewell, & Williams, 2011; Jensen, et al., 2007; Tyndall, Berg, & Colletti, 2011).[71] These characteristics of local biomass markets lead to one of the basic hypotheses of this chapter: heterogeneity between and within local biomass markets will create economic trade-offs with important impacts on the potential supply, distribution, and economics of cellulosic biofuel. The rationale underlying this hypothesis is that heterogeneity will create significant variation in the cost-minimizing production decisions across locations. To test this hypothesis, we apply the theoretical

[70] For construction of Figure 4.2b, the local participation rate and price of biomass were fixed at the values corresponding to the minimum point in Figure 4.2a.

[71] Reasons for variation in willingness to participate in biomass supply within these surveys included, but was not limited to, operator age, environmental concerns, farming experience, market expectations, and opportunity cost of learning a new production process.

model to U.S. switchgrass-based ethanol production, relaxing the assumption of fixed biomass density and price.

4.4 Estimation and data

The data and empirical specification for application of the supply model to bioethanol production from switchgrass are presented in this section. Biorefinery locations considered include crop reporting districts (CRDs) located in rain-fed regions of the U.S.[72]

4.4.1 Estimating local participation rate functions

We derive the fraction of land allocated to biomass production in CRD j based on the following equation:

$$d_j(P_F) = d_{A,j} * d_{S,j}(P_{F,j}) \tag{11}$$

where $d_{A,j}$ is the fraction of total land within district j physically suitable, or able, for biomass production and $d_{S,j}$ is the fraction of suitable land in district j economically sustainable in biomass production at a biomass price of $P_{F,j}$. For baseline analysis, we follow previous literature and limit the acreage that can be converted into switchgrass production (Khanna, Chen, Huang, & Onal, 2011; English, et al., 2010; English, et al., 2006; U.S. DOE, 2011b; de la Torre Ugarte, Walsh, Shapouri, & Slinsky, 2003; Parker, Hart, Tittmann, & Jenkins, 2011). Acreage available for switchgrass production in CRD j (i.e., $d_{A,j}$) is limited to 25% cropland pasture, permanent pasture, failed cropland, and CRP acreage and 10% harvested cropland as determined by CRD land use data.[73] Sensitivity analysis will consider biofuel supply impacts from relaxing these assumptions.

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[72] County-level land area was frequently insufficient to supply enough switchgrass for a commercial scale biorefinery. Rain-fed regions include the Northern and Southern Plains, Corn Belt, Lake States, Delta States, Southeast, Appalachia, and Northeast (Khanna, Chen, Huang, & Onal, 2011).

[73] The updated Billion Ton Report (U.S. DOE, 2011b) allows up to 50% of permanent pasture, 50% of cropland pasture, and 25% of cropland to switch to biomass production in each county. Khanna et al. (2011) allow 25% of harvested cropland, idle cropland (mostly CRP acreage), and cropland pasture to convert into perennial grass production in each CRD. De la Torre Ugarte et al. (2003), English et al. (2006), and English et al. (2010) limit the transition of idle cropland and cropland pasture to bioenergy crops to 40% and 25%, respectively. Parker et

The fraction of available land supplied for biomass production ($d_{S,j}$), or the landowner participation rate, will depend on the fraction of available land for which the price of biomass covers all costs incurred, including opportunity costs, from biomass production. Landowner *i* in district *j* will allocate land to switchgrass production if the price he receives for switchgrass is greater than or equal to the per acre net returns to the current land use plus the costs of switchgrass production.[74] Letting $P_{Opp,j,i}$ denote the landowner's per-acre opportunity cost of biomass cropland and $P_{SG,j,i}$ denote the per-dry ton cost of switchgrass production, the landowner will allocate land into switchgrass production only if

$$P_{F,j} \geq \frac{P_{Opp,j,i}}{Y_{B,j,i}} + P_{SG,j,i}. \qquad (12)$$

The right-hand side of equation (12) represents the minimum per-dry ton price a landowner is willing to accept to allocate land into switchgrass production and will vary between landowners due to differences in P_{Opp}, Y_B, and P_{SG}. In this application, Y_B and P_{SG} are allowed to vary between local biomass markets but fixed within local markets (i.e., $Y_{B,j,i} = Y_{B,j}$ and $P_{SG,j,i} = P_{SG,j}$ for all i in district *j*), while $P_{Opp,j,i}$ is allowed to vary between potential suppliers within the same local biomass market. By limiting within-region supplier heterogeneity to differences in opportunity cost, variation in the local landowner participation rate ($d_{S,j}$) depends only on the distribution of opportunity costs within the district. As a result, the local landowner participation rate in district *j* will only vary with the price paid by the biorefinery to cover landowner opportunity cost ($P_{Opp,j}$) or

$$d_j = d_{A,j} * d_{S,j}\left(P_{Opp,j}\right), \qquad \text{where} \quad \frac{\partial d_{S,j}}{\partial P_{Opp,j}} \geq 0. \qquad (13)$$

Data of the quantity and opportunity cost of land likely to move into switchgrass production is needed to identify the true function $d_{S,j}\left(P_{Opp,j}\right)$ for each location. These data do not exist and so, in their absence, we use utilize information from Conservation Reserve Program (CRP) contract

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al. (2011) allow 25% and 50% of cropland idle and cropland pasture to convert to energy crop production for low and high assumptions, respectively.

[74] The landowner's decision is considered prior to investment in switchgrass production and therefore all switchgrass production costs, including establishment costs, are assumed variable.

offers. These data are unique in that they include all contracts offered, included those not accepted for enrollment. The CRP offers data provide information, including acreage quantities and offered rental rates, from landowners willing to forgo current agricultural production in exchange for an annual fixed payment.[75] The dataset of CRP offers serves as revealed information on the heterogeneity in opportunity cost of potential dedicated biomass cropland within each region.[76]

The CRP offers data used in this analysis are from the general signup 26, which occurred during 2003. General signups are characterized by a competitive offer-submission process. An offer submitted by a landowner includes the per-acre rental rate – the bid – at which the landowner is willing to idle his cropland from agricultural production and install one or more conservation practices for the next 10 years. If accepted, the landowner receives a fixed stream of payments at the bid rate for a 10-year period. General signup enrollments are typically whole field enrollments as opposed to buffers, filter strips, field streams, etc., which are largely enrolled in CRP continuous signup (Jacobs, 2010).[77] We adjust the landowners' bids from 2003 to make them comparable to the switchgrass production costs, which are in 2007 dollars, by applying a multiplicative factor equal to the CRD average increase in CRP rental rates between 2003 and 2007.[78]

The CRP offers data provide the price at which a landowner is willing to idle crop production and put the land to a conservation cover. We use this information as a proxy for the price necessary to induce a production shift to an alternative use such as switchgrass production (i.e., P_{Opp}). For each CRD within a rain-fed region and with at least 20 offers to enroll in CRP general signup 26 (shown in Figure 4.3), a nonparametric kernel density estimator was used to construct a cumulative distribution

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[75] A CRP offer is a "contract between a landowner and the United States Department of Agriculture (USDA) whereby the landowner proposes to idle from traditional agricultural production a parcel of land on which he will install certain conservation practices in exchange for an annual rental payment" (Jacobs, 2010, p. 195).

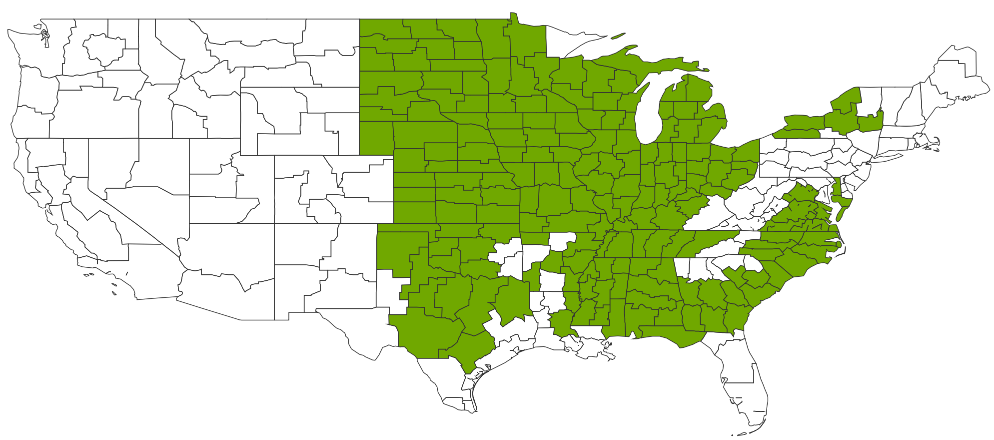
[76] The authors gratefully acknowledge the USDA FSA and Economic and Policy Analysis Staff for access to the CRP data.

[77] CRP continuous signup targets "the most degradation-prone, environmentally sensitive and marginally productive agricultural land" (Jacobs, 2010, p. 120). Therefore, these types of land are not included in the data used for our analysis.

[78] A request for more recent CRP offers data or summary statistics for updating purposes has been submitted.

function (CDF) of the offered rental rates within the district weighted by acreage offered for enrollment.[79] The fitted CDF provides an estimate of the fraction of offered land available at or below each per acre payment amount. As an example, Figure 4.4 provides the fitted CDF and corresponding probability density function (PDF) of offered rental rates per acre for a select district. We use the fitted CDF of CRP offers within each district as a proxy for the CRD-specific function $d_{S,j}(P_{Opp,j})$. Therefore, the revealed information on landowner's willingness to forgo current agricultural production in exchange for an annual fixed payment provided by the CRP offers data allows us to identify heterogeneity in the opportunity cost of potential dedicated biomass cropland within each region that, to our knowledge, has not been done before.

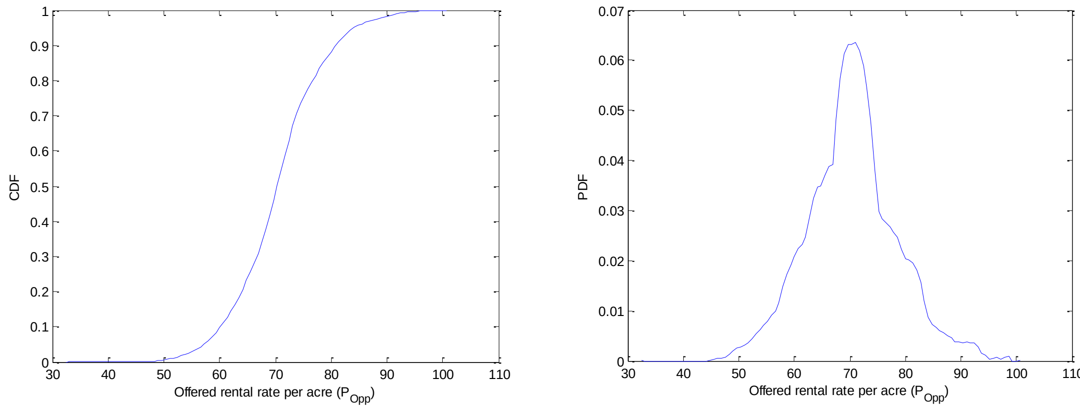
Figure 4.3 – Rain-fed CRDs with at least 20 offers to enroll in CRP general signup 26



[79] The Epanechnikov kernel function, which is both efficient (i.e., minimizes the mean integrated square error) and computationally compact, is used to derive the fitted distribution functions (Silverman, 1986; Cameron & Trivedi, 2005). The rainfed regions include 243 of the 317 total CRDs. The number of CRDs reduces to 186 when restricted to those with at least 20 offers to enroll in CRP general signup 26. Silverman (1986) argues at least 4 data points are needed for an accurate nonparametric estimate of a one variable distribution. Others have argued Silverman's minimum values may be an underestimate. Therefore, we use a conservative cutoff value of 20 based on the minimum data points suggested by Silverman for a two-dimensional distribution.

Figure 4.4 – Cumulative and probability density functions of CRP offers from a single district in general signup 26

(a). CDF (b). PDF



We make two important assumptions to estimate the relationship between the participation rate and price of feedstock. First, we maintain the Khanna et al. (2011) assumption that yields are unaffected by soil quality within local markets and production costs (P_{SG}) and yields (Y_B) are constant within each district. In actuality, production costs and yields may vary within local markets due to soil quality differences as well as differences in supplier experience, education, access to capital, etc. (Lichtenberg, 2002; Tyndall, Berg, & Colletti, 2011). We attempt to limit soil quality differences within regions by restricting the quantity and type of land able to shift into switchgrass production (that is, limit land types within d_A). We capture soil quality differences by accounting for variation in P_{Opp}. Yet, by fixing P_{SG} and Y_B within markets, biomass supplier heterogeneity is underestimated. Heterogeneity of P_{SG} and Y_B within local biomass markets is something we hope to investigate in future research. However, underestimating supplier heterogeneity does not restrict us from achieving the primary analysis goal. We are not attempting to perfectly identify local biomass supply curves or the exact biorefinery locations, but rather are illustrating and evaluating the economic trade-offs and potential market impacts from biomass supplier heterogeneity between and within biomass markets. Capturing heterogeneity in land opportunity cost allows us to examine these effects.

Second, we assume the heterogeneity in CRP offers within each district can be used as a proxy for heterogeneity in opportunity cost of potential switchgrass cropland (P_{Opp}) within the district. We assert this is a reasonable assumption for several reasons. First, the stand length for switchgrass production is approximately 10 years, equivalent to the contract length for the general signup CRP. Therefore, the offers dataset contains revealed prices from landowners whose decisions to remove land from its current activity were based on a time frame consistent with a commitment to switchgrass production. Second, the CRP targets erodible and environmentally sensitive cropland (Mapemba L. , Epplin, Taliaferro, & Huhnke, 2007). Switchgrass was selected as the model bioenergy crop, at least in part, due to its relative productivity on marginal cropland (Wright & Turhollow, 2010). Third, switchgrass production provides many of the conservation benefits landowners might seek through CRP participation, such as reduced soil erosion and wildlife benefits (Mapemba L. , Epplin, Taliaferro, & Huhnke, 2007). Finally, it has been suggested that characteristics of switchgrass production may lead to contracts/relationships between a biorefinery and landowners similar to those between the government and CRP enrollees (Epplin, 2009). Without a dataset of the quantity and opportunity cost of land within each district likely to move into switchgrass production, we believe the offers data provide a reasonable approximation based on revealed landowner variation in willingness to shift current land use.

We posit that CRP offers data can contribute to understanding the opportunity cost faced by landowners of moving from row-crop production to switchgrass production; however, their use in this manner requires some discussion of the ways in which they may not be a precise indicator. There are many factors that lead landowners to enroll in the CRP and on which their bid rate may be conditioned. Landowners may have references for providing environmental benefits and other amenities, such as hunting benefits, from which the benefits from switchgrass production may not equal the benefits from CRP enrollment. For example, annual switchgrass harvest may limit desired environmental benefits (e.g., soil compaction from machinery), while a limited switchgrass harvest window may reduce potential hunting benefits. Some landowner's also might desire the "absentee landowner" opportunity provided by CRP enrollment. In this case, the biorefinery may need to develop a more integrated system and contract for land access as opposed to biomass and assume responsibility of biomass production (e.g., plantation model). Finally, a literature exists on the potential for landowners to submit bids in excess of their reservation wage in order to extract rent from the CRP (Kirwan, Lubowski, & Roberts, 2005; Marra & Vukina, 1998; Miranda, 1992; Reichelderfer & Boggess, 1988; Schoemaker, 1989; Smith, 1995; Vukina, Zheng, Marra, & Levy, 2008). To the extent that landowners behave in this manner, offers do not necessarily capture the landowner's minimum willingness to accept but something greater. Without an appropriate method to identify which, if any, bids fall into this category, we do not attempt to correct for potential over-bids and use the observed values to represent the value at which landowners are willing to forgo the current land use.

4.4.2 Data and parameter assumptions

Data for the "baseline" biorefinery are from Kazi et al. (2010b) who provide costs for a proposed 53.4 million gallon per year (mgy) biorefinery using a biochemical process (co-current dilute acid prehydrolysis and enzymatic hydrolysis).[80] Capital costs are assumed to exhibit economies of scale. Capital costs for the proposed biorefinery are \$375.9 million or approximately \$0.72 per gallon (C_{P,Q_0}) when amortized over a 20 year plant life at an interest rate of 8% and assuming a biofuel yield of 69.2 gallons per dry short ton of switchgrass (Y_O). A baseline value of 0.75 is assumed for the biorefinery economies of scale factor (k). For simplicity, all other processing costs are considered to be independent of plant size. Total operating costs, including co-product credit from

[80] The biorefinery outlined in Kazi et al. (2010a) is for a corn stover to ethanol biorefinery. Biorefinery costs (C_{P,Q_0}, $C_{P,N}$) are assumed to be similar for switchgrass and stover conversion with the same platform technology. To the extent we underestimate biorefinery costs that exhibit economies of scale (C_{P,Q_0}), we will underestimate the optimal biorefinery capacity. $C_{P,N}$ is independent of biorefinery capacity and therefore will not impact the cost-minimizing biorefinery capacity. Yet, to the extent we underestimate $C_{P,N}$, we will underestimate the average biofuel production cost at all capacity levels.

excess electricity but excluding capital depreciation and average return on investment, are approximately \$1.40 per gallon ($C_{P,N}$).

Switchgrass production costs per dry ton (P_{SG}) are taken from Khanna et al. (2011).[81] For switchgrass yields (Y_B), we assume 75% of the simulated values from the crop productivity model MISCANMOD reported by Khanna et al. (2011). The lower yield assumption reflects recent field and plot trials and accounts for lower collection efficiency and additional handling losses (Rosburg & Miranowski, 2011). Switchgrass production costs per dry ton are adjusted to reflect the lower per acre yield assumption.[82] Due to low switchgrass yields (< 0.60 dt/acre) and high biomass production costs (> \$280/dt), four CRDs located in south and west Texas are excluded. This reduces the total number of districts in the analysis to 182.

Long term biomass storage costs (*S*), including loading and unloading costs, are \$15.50 per dry ton based on values reported in Miranowski & Rosburg (2010a). The variable cost for transportation (*t*) is \$0.71 per dry ton per mile as assumed in Wright & Brown (2007). Table 4.1 summarizes the data and parameter assumptions used to solve the biorefinery optimization problem for each district. Key parameter assumptions will be subjected to sensitivity analysis and discussed later.

[81] All biomass values are reported in short tons.
[82] An illustration of the switchgrass production cost (\$ per-dry ton) and yield (dry tons per-acre) for each CRD within the analysis can be found in Appendix Figures C.4.1 and C.4.2, respectively.

Table 4.1 – Biorefinery and feedstock cost parameter assumptions

	Parameter	Value	Source(s)
Biorefinery			
	Technology	Biochemical	Kazi et al. (2010b)
	Q_0	53.4 mgy	Kazi et al. (2010b)
	C_{P,Q_0}	$0.72/gal	
	Total cost	$375.9 million	Kazi et al. (2010b)
	Debt financing	100%	Wright & Brown (2007)
	Years	20 years	Wright & Brown (2007)
	Interest rate	8%	Wright & Brown (2007)
	$C_{P,N}$	$1.40/gal	Kazi et al. (2010b) [83]
	Y_O	69.2 gal/dt	Kazi et al. (2010b)
	k	0.75	Several[84]
Feedstock			
	P_{SG}	CRD specific	Khanna et al. (2011) scaled by yield assumption
	Y_B	CRD specific	75% yield value from Khanna et al. (2011)
	S	$15.50/dt	Miranowski & Rosburg (2010a)[85]
	t	$0.71/dt/mile	Wright & Brown (2007)
	γ	0.0189	French (1960)
	d_A 25% cropland pasture 25% permanent pasture 25% CRP acreage 25% failed cropland 10% harvested cropland	CRD specific	2007 Agricultural Census data (NASS) and CRP enrollment data (USDA – FSA)
	$d_s(P_{Opp})$ and P_{Opp}	CRD-specific function	CRP offers data

[83] Sum of operating costs reported by Kazi et al. (2010a). Includes co-product credit but excludes capital depreciation and average return on investment.
[84] Cameron, Kumar, & Flynn (2007b), de Wit, Junginger, Lensink, Londo, & Faaij (2010), Gan (2007), Kaylen, Van Dyne, Choi, & Blasé (2000), Kumar, Cameron, & Flynn (2003), Leboreiro & Hilaly (2011), Searcy & Flynn (2009), and Wright & Brown (2007a).
[85] Reported value includes storage cost and distance fixed costs (loading).

4.4.3 CRD acreage constraint

To avoid double-counting acreage and overestimating potential biofuel supply, the biorefinery is limited to acreage only within the CRD. The maximum capture radius is set at the capture radius for a biorefinery located in the center of the CRD with a circular capture region and total land area equal to the total land area within the district (equation 14).

$$r_{max,j} = \sqrt{\frac{\text{Square miles in CRD j}}{\pi}}\,. \qquad (14)$$

Combining equation (14) with the model equation for capture radius (equation 2) yields the following constraint:

$$Q_j \leq \left(\frac{r_{max,j}}{\gamma}\right)^2 \times \left[Y_O \times Y_{B,j} \times d_{A,j} \times d_{s,j}\left(P_{Opp,j}\right)\right]. \qquad (15)$$

4.4.4 Empirical specification and estimation procedure

The empirical analysis is conducted in three steps. First, the function $d_{S,j}(P_{Opp,j})$ is estimated for each district using the CRP offers data. Second, the CRD-specific estimates for $d_{S,j}(P_{Opp,j})$ are incorporated within a non-linear mathematical programming model to identify the cost-minimizing production decisions for a biorefinery in each CRD. The model is limited to one biorefinery per district for the baseline results. Given the parameter assumptions and constraints outlined in the previous subsections, the non-linear mathematical programming model solves equation (16) for each CRD (j). The model simultaneously derives the minimum total cost per gallon of biofuel production (C_j), minimum efficient capacity (Q_j), and per acre opportunity cost payment ($P_{Opp,j}$) at the cost-minimizing landowner participation rate [$d_{S,j}(P_{Opp,j})$].

$$\min_{Q_j,P_{Opp,j}} \; C_j = \; C_{P,N} + C_{P,Q_0}\left[\frac{Q_j}{Q_0}\right]^{k-1} + \frac{1}{Y_O}\left[P_{SG,j} + \frac{P_{Opp,j}}{Y_{B,j}} + S + t\gamma\sqrt{\frac{Q_j}{Y_O\,Y_{B,j}d_{A,j}d_{s,j}(P_{Opp,j})}}\right] \tag{16}$$

subject to

$$\frac{\partial d_{s,j}(P_{Opp,j})}{\partial P_{Opp,j}} \geq 0$$

$$d_{s,j}(P_{Opp,j}) \in [0,1]$$

$$Q_j \leq \left(\frac{r_{max,j}}{\gamma}\right)^2 \times \left[Y_O \times Y_{B,j} \times d_{A,j} \times d_{s,j}(P_{Opp,j})\right]$$

$$Q_j, P_{Opp,j} \; \geq 0$$

In the third and final step, the CRD minimum costs of biofuel production and cost-minimizing biorefinery capacities are combined to generate a stepwise aggregate supply curve for ethanol.

4.5 Results

This section presents results from the empirical application to switchgrass ethanol production. We begin with CRD-level results based on the cost-minimizing plant size, capture radius, and price of biomass.[86] CRD supplies are combined to develop the aggregate supply curve. The estimated aggregate supply curve is used to identify the least cost of meeting the RFS2 cellulosic biofuel mandates and other production targets. The estimated supply curve in then compared to estimated supply curves derived with fixed land opportunity costs and participation rates. Sensitivity analysis follows for key model and parameter assumptions.

4.5.1 Baseline model results

Figure 4.5 illustrates the minimum cost per gallon of ethanol (*C*) produced in each CRD. Estimated costs range from \$3.19 to \$4.57 per gallon.[87] The lowest cost ethanol is produced at a 117 mgy biorefinery located in northeast Texas. The CRDs numbered in Figure 4.5 represent the 10 least-

[86] The CRDs considered in the analysis include the 182 CRDs located in rain-fed regions with at least 20 offers to enroll in CRP signup 26.
[87] All per-gallon estimates are reported on a per-gallon ethanol basis. Other studies report biofuel cost estimates on a gasoline-equivalent basis. Per-gallon ethanol prices can be converted into a gasoline-equivalent basis using an energy equivalence factor. One gallon of ethanol provides approximately two-thirds the energy content of one gallon of conventional gasoline. The reported ethanol cost range is equivalent to a range of \$4.80-\$6.85 per gallon gasoline equivalent.

cost locations and are located in Texas, Oklahoma, and Kansas.[88] Relatively low ethanol costs in these districts are driven by a combination of higher biomass yields, lower land opportunity costs, and a greater amount of suitable land for biomass production. The model results suggest ethanol production would first develop at these locations then shift towards higher cost locations in the Northern and Southern Plains, Delta, and Appalachia regions.

Figure 4.5 – Estimated minimum total cost ($/gallon) of switchgrasss ethanol by CRD

(Numbers identify the 10 biorefinery locations with lowest per gallon cost where 1 represents the least cost location)

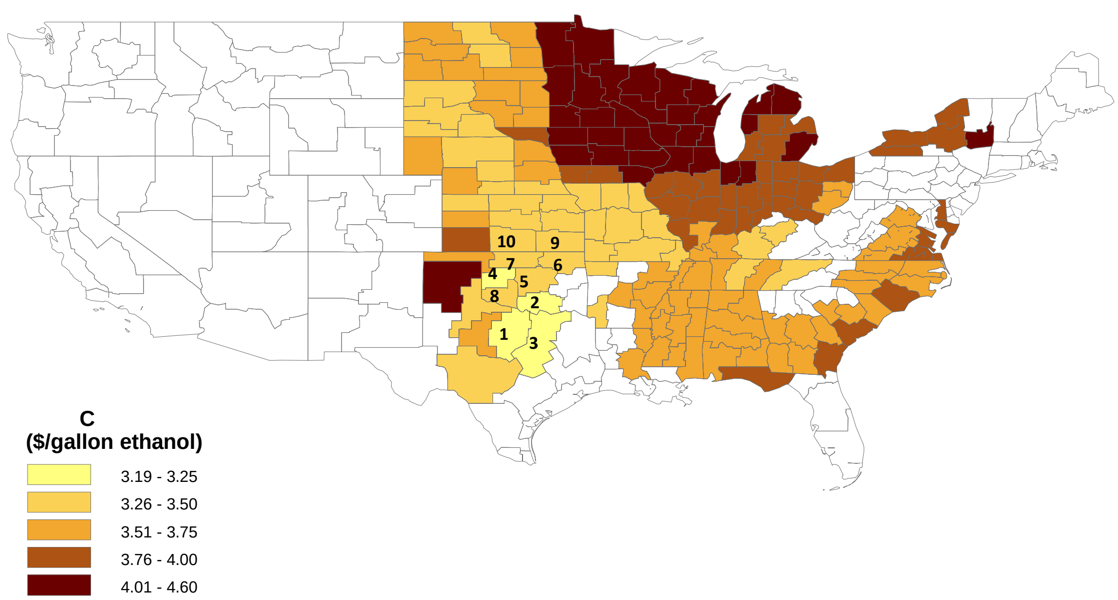


Figure 4.6 provides the aggregate ethanol supply curve constructed from the CRD cost-minimizing supplies. Although the aggregate supply curve appears relatively smooth, the estimated function is a stepwise curve with each step corresponding to a different biorefinery location. If each

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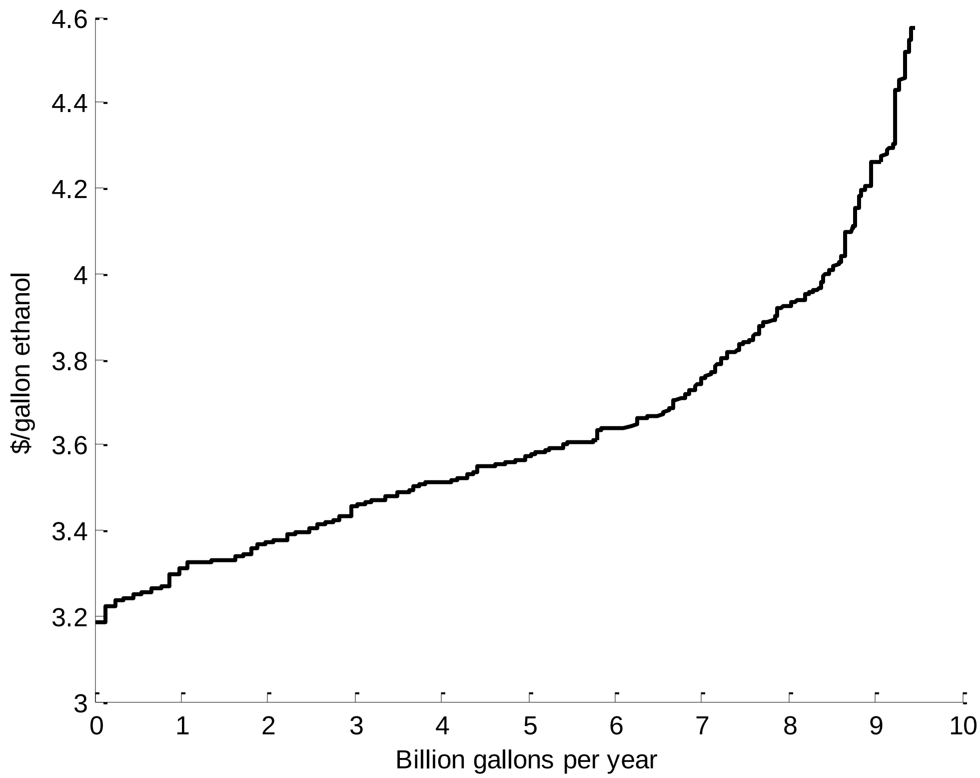
[88] An illustration analogous to Figure 4.5 for the cost-minimizing biorefinery capacity (Q^*) in each CRD can be found in Appendix Figure C.4.3.

district has a biorefinery at the cost-minimizing capacity, estimated total production reaches 9.5 billion gallons per year (bgy).

Figure 4.6 – Estimated ethanol supply curve from switchgrass



The ethanol supply curve can be used to identify the market conditions needed or costs to meet the RFS2 cellulosic biofuel mandates and other production targets with switchgrass. Table 4.2 provides three alternative costs or market conditions needed to support switchgrass production between 2 and 8 bgy. First, the ethanol supply curve provides an estimate of the breakeven price of biofuel production (Table 4.2, Row 1). Second, the breakeven ethanol price can be translated into a long-run price of oil needed for markets to support biofuel production by assuming a simple linear relationship between the price of ethanol and price of oil $\left[P_{ethanol} = 0.667 \times \left(\frac{P_{Oil}}{29}\right)\right]$ (Table 4.2, row 2). Third, a lower market price of oil would be needed to support biofuel production if the government covers a portion of the biofuel costs through a tax credit to cellulosic biofuel producers

(Table 4.2, row 3).[89] While the price of oil needed to support the market is lower with the tax credit, the total cost is unchanged given the cost of government support.

Table 4.2 – Market conditions needed to support U.S. biofuel production with switchgrass ethanol
(2007$)

Production (bgy)	**2**	**4.25**	**6**	**8**
Cellulosic ethanol price ($/gallon)	3.37	3.52	3.64	3.92
Oil price ($/barrel)	147	153	158	171
Oil price with tax credit ($/barrel)	103	109	114	127

Note: Values are wholesale prices

A cellulosic ethanol price of $3.52 per gallon ($5.30 per gallon gasoline equivalent) or a long-run oil price above $150 per barrel is needed for switchgrass-based ethanol to satisfy the 2016 cellulosic biofuel mandate of 4.25 bgy. With extension of the current cellulosic biofuel producer's tax credit of $1.01 per gallon, the long-run oil price needed for the market to support 4.25 bgy reduces to $109 per barrel.[90] At its record peak in July 2008, the price of crude oil reached $145 per barrel and then fell to around $30 per barrel by December 2008. The 2012 Annual Energy Outlook forecasts oil prices of $129 per barrel in 2022 and $145 per barrel in 2035 in their reference scenario (2010$) (U.S. EIA, 2012a).

We hypothesized heterogeneity between and within local biomass would create significant variation in the cost-minimizing decisions across CRDs. The summary statistics in Table 4.3 support this hypothesis. Minimum efficient capacities range from 9 to 117 mgy with a 52 mgy average capacity, while the capture radius is 35 miles on average with a range between 22 and 51 miles.[91] The

[89] The cellulosic biofuel producer's tax credit provided by the 2008 Farm Bill is scheduled to expire on December 31, 2012.
[90] A graph of the quantity of breakeven production with and without the tax credit over a range of oil prices can be found in Appendix Figure C.4.4.
[91] The CRD acreage constraint imposed to avoid double-counting (equation 15) was binding for about 20% of the CRDs but prevalent in higher cost locations. The constraint was non-binding for CRDs that contribute the first 4.4 bgy of ethanol; acreage within these CRDs was able to satisfy the feedstock demand for the minimum efficient scale biorefinery capacity. A binding acreage constraint within select CRDs has minimal effect on the

landowner participation rate ranges between 47% and 100% with opportunity cost between $4 and $58 per dry ton.

Table 4.3 – Summary statistics of cost-minimizing biorefinery decisions

	Q	r	d_S	$\frac{P_{Opp}}{Y_B}$	C
	(mgy)	(miles)		($/dt)	($/gallon)
All biorefineries (182)					
Average	52	35	90.7%	18.6	3.73
Median	46	35	94%	15	3.67
Range	9 – 117	22 – 51	47-100%	4 – 58	3.19 – 4.57
10 most cost-efficient locations (average)	107	29	98%	9.8	3.25
10 least cost-efficient locations (average)	30	39	74%	43	4.43

To further illustrate the variation in cost-minimizing decisions, consider the 10 most cost-efficient and 10 least cost-efficient locations. In the former, high participation rates can be achieved at a relatively low cost. These locations capitalize on the presence of low opportunity cost land by building large-scale biorefineries (107 mgy average) with high local participation rates (98% average). The average opportunity cost to achieve high participation is only $9.80 per dry ton. These locations also benefit from larger amounts of available land for biomass production (i.e., higher d_A) and higher biomass yields resulting in a below average capture radius (29 miles). In contrast, high landowner participation rates are costly within the 10 least cost-efficient locations. An average land opportunity cost payment of $43 per dry ton is needed to achieve an average participation rate of 74%. With lower landowner participation, biomass yields, and density of available land for biomass production, these biorefineries transport biomass from more distant locations (39 miles) despite a lower feedstock demand (30 mgy capacity).

The summary statistics in Table 4.3 provide insight into the spatial variation in cost-minimizing decisions but do not provide a complete picture of the CRD-level economic trade-offs

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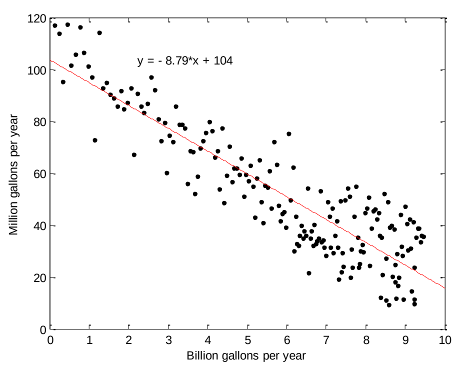
estimated aggregate supply curve. A comparison of the estimated aggregate supply curve with and without the acreage constraint is provided in Appendix Figure C.4.5.

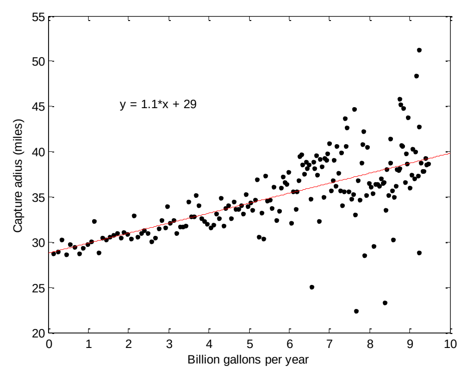
underlying the estimated aggregate supply curve. The cost-minimizing biorefinery decisions along the supply curve depicted in Figure 4.7 make it possible to take a closer look at CRD-level trade-offs. Each dot in Figures 4.7a – 4.7c represents the cost-minimizing decision for the biorefinery built at the corresponding aggregate production level (or price of ethanol).[92] Least cost biofuel expansion is characterized by three trends: decreasing capacity (Figure 4.7a), increasing biomass transportation distance (Figure 4.7b), and decreasing landowner participation rate (Figure 4.7c). These trends are a result of locational differences in the economics of biomass production.

Figure 4.7 – Biorefinery cost-minimizing decisions along the aggregate supply curve

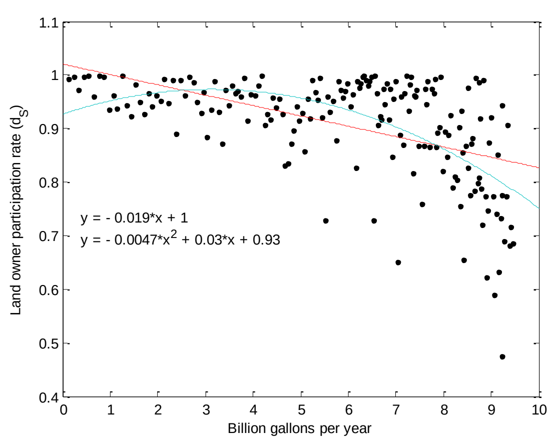
(a). Biorefinery capacity (*Q*)



(b). Capture radius (*r*)



(c). Participation rate (d_S)



[92] Appendix Figure C.4.6 provides analogous figures for biomass yield, biomass production costs, density of available land for biomass production, opportunity cost per acre, and opportunity cost per ton of switchgrass.

Three key determinants of locational differences in biomass production include biomass yield, amount of suitable land for biomass production, and land opportunity costs. Cost efficient biorefineries are located in regions with higher biomass yields. All else constant, a lower biomass yield increases the cost of biofuel in three ways. First, the biorefinery would have to travel farther to meet a given feedstock demand. Second, a lower yield increases the opportunity cost per dry ton of biomass. Third, biomass production costs increase as fixed costs of production are spread over fewer units of output. As a result, the expansion of biofuel production onto lower yielding areas not only increases the cost of biofuel production but leads to smaller capacity biorefineries with larger capture regions and lower participation rates.

The fraction of available land for switchgrass production also is falling with cumulative production. The decrease in suitable land for biomass production has similar effects on capture region distance as a decrease in biomass yield. Therefore, biofuel market expansion into areas with lower land availability is another contributor to declining biorefinery capacity and increasing biomass hauling distance.

As biofuel production expands into areas with higher opportunity cost land, the cost-minimizing decision is to operate at a lower point along the $d_S(P_{Opp})$ curve. The inclusion of an endogenous participation rate is able to dampen but does not reverse the upward trend in per acre opportunity costs. Even with lower participation rates, per acre opportunity costs still are higher. Similar to lower switchgrass yield and available land, biofuel expansion into areas with high opportunity cost land increases the cost of biofuel production but also supports the upward trend in capture radius and downward trends in the participation rate and biorefinery capacity.

By accounting for these spatial differences within and between biomass suppliers, we capture important economic trade-offs in biomass production, transportation, and conversion. Ultimately, these local trade-offs drive the convex nature of the aggregate supply curve in Figure 4.6 and, as will be shown in the following subsection, ignoring these trade-offs may lead to an under- or over-estimate of the quantity and cost of biofuel production.

4.5.2 Impact of fixed versus endogenous participation rates

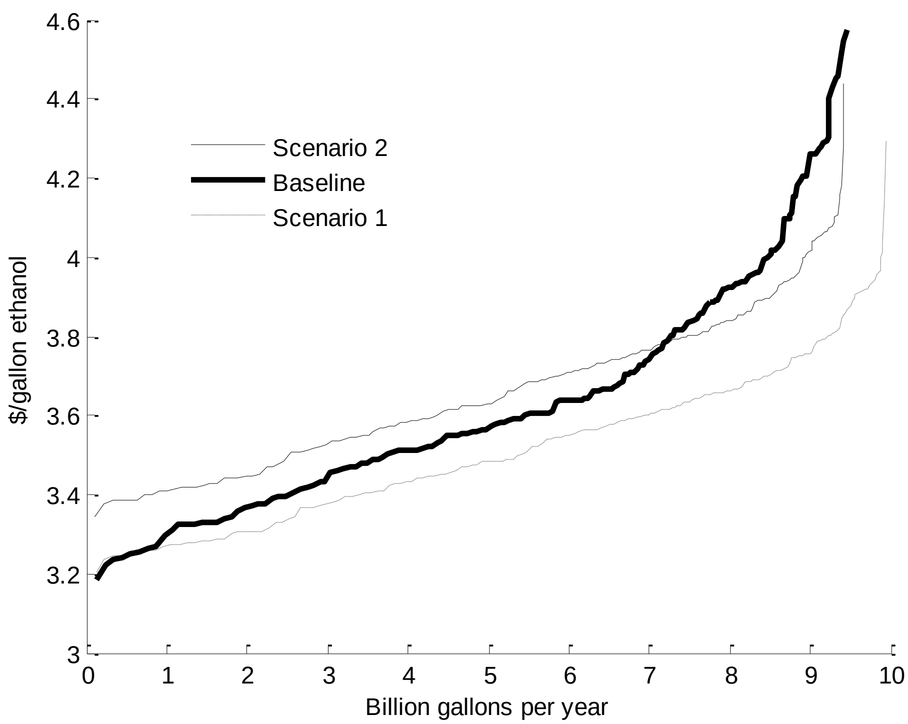
Heterogeneity between local landowners enters the empirical model through location-specific participation rate and opportunity cost functions, $d_s(P_{Opp})$. Previous studies have assumed exogenous, fixed values for participation rate and opportunity cost payment. Unless the fixed participation rate and opportunity cost are set exactly at the cost-minimizing values for each potential location, a fixed analysis will over- or under-estimate the cost-minimizing production conditions. We first consider two hypothetical scenarios which are constructed on the premise that, without data on supplier heterogeneity, researchers are likely to use some sort of 'average values.' Second, we compare the baseline results to those using participation rate and opportunity cost assumptions found in previous literature.

Two hypothetical scenarios for a fixed analysis

Two hypothetical scenarios are constructed on the premise that, without data on supplier heterogeneity, researchers are likely to use some sort of 'average values.' In Scenario 1, the fixed participation rate and opportunity cost payment are set equal to the average values for the 10 least-cost biorefinery locations. In other words, Scenario 1 extrapolates the best-case conditions to all CRDs. The participation rate is fixed at 98% and opportunity cost payment is fixed at $9.80 per dry ton. Scenario 2 sets the fixed participation rate and opportunity cost payment equal to the average values from all 182 biorefinery locations. Scenario 2 represents the mean values for participation rate and opportunity cost payment of 90.7% and $18.60 per dry ton, respectively.

Figure 4.8 graphs the ethanol supply curves from the baseline and two fixed analysis scenarios.[93] Scenario 1 underestimates the cost of ethanol production (beyond 1 bgy) and overestimates total production capacity (~0.5 bgy). Scenario 2 overestimates the cost of switchgrass ethanol production for lower aggregate production levels but underestimates the cost of production for aggregate production above 7.25 bgy. An important observation from Figure 4.8 is the additional variation in the supply curve with an endogenous participation rate relative to fixed analysis scenarios. The supply curves for Scenario 1 and 2 are relatively flat compared to the baseline supply curve (up to 9 bgy). By accounting for observed heterogeneity in potential biomass suppliers, the baseline model is able to trade-off economies in biomass production, transportation, and conversion not captured by the fixed value scenarios.

Figure 4.8 – Estimated aggregate supply curve for the baseline and fixed analysis scenarios



[93] With a fixed biomass density and price of biomass value for each CRD, the optimistic and average scenarios are estimated using the simplified biorefinery objective function discussed in section 4.3.4 and outlined in Appendix C.3.

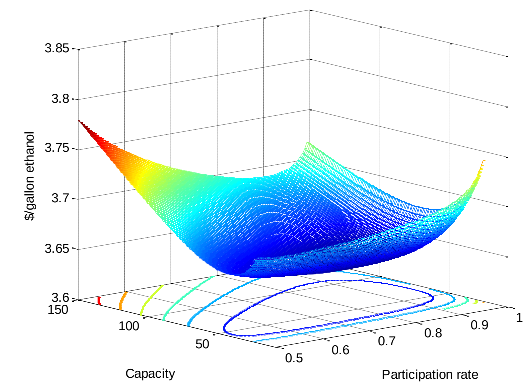
Differences in the estimated aggregate supply curve stem from differences in CRD-level cost-minimizing production decisions. Location-specific biomass production conditions make it impossible for a single fixed value to be set at the cost-minimizing value for all CRDs. As a result, the impact on the estimated cost and capacity from imposing fixed values will not be uniform across locations.

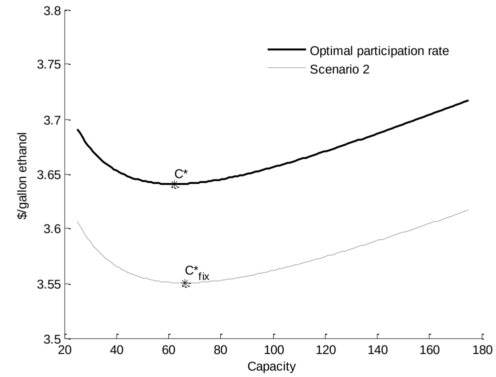
For example, Figure 4.9 compares the impact of Scenario 2 on the estimated ethanol cost and plant capacity in three CRDs located in the same state. CRD A has relatively high per acre opportunity costs and low switchgrass yields. The minimum of CRD A's cost surface is at a lower participation rate and higher opportunity cost payment than assumed in Scenario 2. As a result, Scenario 2 underestimates the cost of production and overestimates the minimum efficient capacity. For CRD B, Scenario 2 assumptions are close to the values at the minimum point on CRD B's cost surface and the fixed approach has minimal impact on the estimated cost and capacity. The third location, CRD C, has relatively low opportunity costs. Scenario 2 assumes a lower participation rate and higher opportunity cost payment and overestimates the cost of production and underestimates the minimum efficient capacity. Although the CRDs in Figure 4.9 are located in the same state, they experience different impacts in terms of the estimated cost and quantity of least-cost production from the Scenario 2 assumptions. Moving beyond CRDs within the same state, the variation in the cost and quantity impacts from a fixed analysis increase as locations differ more in terms of switchgrass potential and land opportunity cost.

Figure 4.9 – Sensitivity of average cost of biofuel production ($/gallon ethanol) and minimum efficient capacity to Scenario 2 assumptions for three CRDs in the same state

CRD A

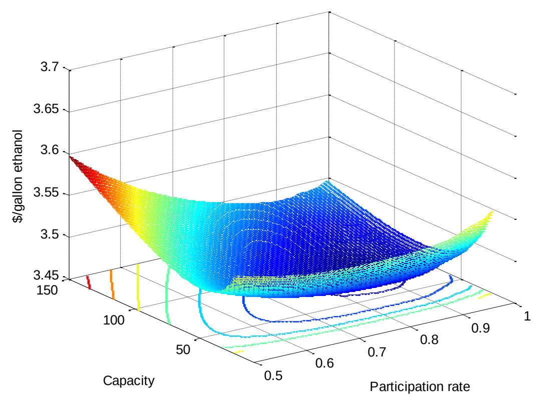
Endogenous Participation Rate | **Fixed participation rate and opportunity cost**

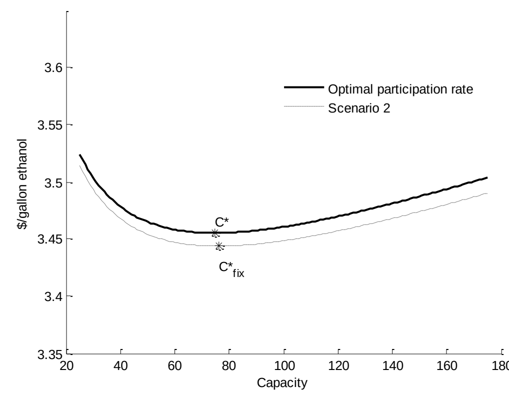




CRD B

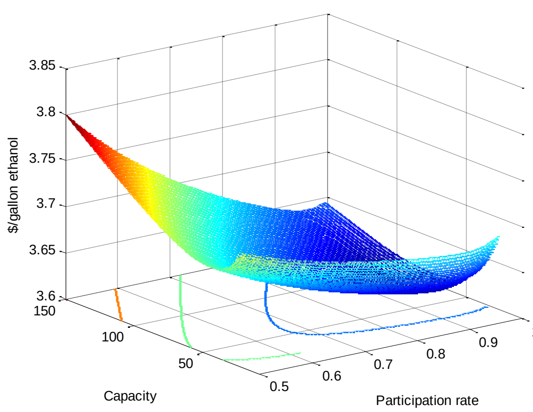
Endogenous Participation Rate | **Fixed participation rate and opportunity cost**

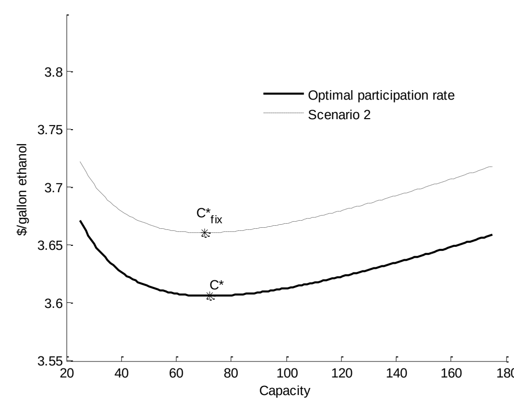




CRD C

Endogenous Participation Rate | **Fixed participation rate and opportunity cost**





Comparison with previous literature

Previous literature has used a variety of assumptions regarding landowner participation in biomass supply and land opportunity cost. We compare baseline model results to those derived using the fixed assumptions from four recent studies: Huang et al. (2009), Popp & Hogan (2007), Brechbill & Tyner (2008a), and Khanna, Chen, Huang, & Onal (2011). Table 4.4 summarizes the participation rate and opportunity cost assumptions from each analysis. These studies differ in several important ways beyond the participation rate and land opportunity cost assumptions. In order to focus on the impact of interest, other paper-specific assumptions are not considered. Baseline model assumptions and data are used for all other model parameters.

Table 4.4 – Switchgrass land density and opportunity cost assumptions

Model	**Fraction of land in switchgrass (*d*)**	**Opportunity cost (P_{Opp})[94]**
Baseline	$d_A*d_s(P_{Opp})$	$d_s^{-1}(P_{Opp})$
Brechbill & Tyner (2008a)[95]	$0.75*d_A$	\$70/Y_B
Huang et al. (2009)	0.075	\$10*($d_{grassland}$) + \$15.4*($d_{cropland}$)
Khanna et al. (2011)[96]	$1.0*d_A$	Net returns from least profitable crop (CRD-specific)
Popp & Hogan (2007)	0.175	\$75/Y_B

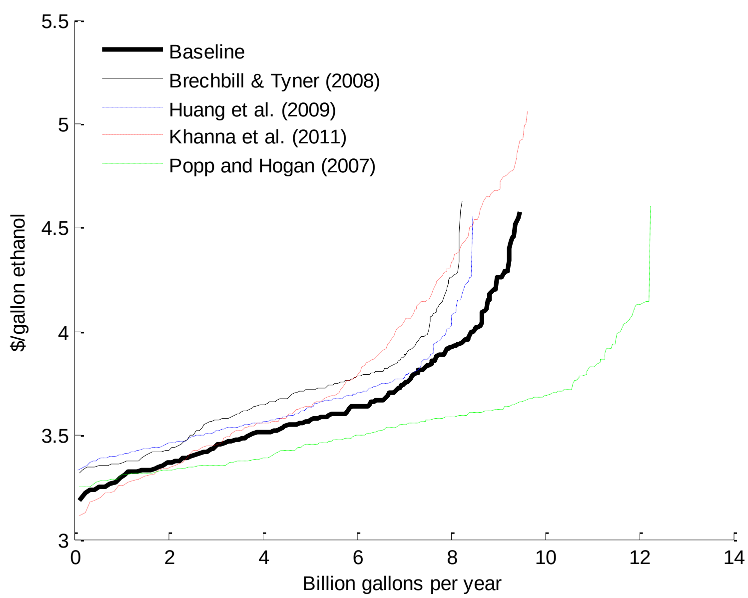
Figure 4.10 graphs the estimated aggregate supply curve from the baseline model along with the estimated supply curves using the fixed participation rate and opportunity cost assumptions from the four papers considered. The assumptions used by Huang et al. (2009) and Brechbill & Tyner (2008a) result in estimated supply curves with similar curvature to the baseline model but with higher cost estimates. The estimated supply curves using the assumptions reported in Popp & Hogan (2007) and Khanna et al. (2011) originate at a price near the baseline supply curve but increase at a slower

[94] Baseline yield assumptions and data are used to convert all per acre opportunity costs into per ton values.
[95] Brechbill & Tyner (2008a) derive d_A based on Indiana land use data. To focus on the impact of different participation rates, we maintain our assumption for d_A and use the 75% participation rate assumption. Although not evaluated here, Brechbill & Tyner (2008a) also considered a participation rate of 50%.
[96] Khanna et al. (2011) assume that 25% of cropland, pastured cropland, and cropland idle is able to switch into perennial grass production (i.e., d_A). Similar to the Brechbill & Tyner (2008a) assumptions, we maintain our assumption for d_A and use the reported participation rate.

and faster rate, respectively. The slower rate of increase in the Popp & Hogan (2007) supply curve is driven by higher participation rate and lower opportunity cost assumptions. These assumptions result in lower cost biofuel produced at larger capacity biorefineries.

Unlike the other three studies, Khanna et al. (2011) allow for different land opportunity costs between CRDs. Yet, the opportunity cost is assumed fixed for all suppliers within each CRD. The baseline model relaxes this assumption through CRD-specific participation rate and opportunity cost functions. That is, biorefineries located in areas with higher opportunity cost land have the flexibility to trade-off landowner participation for a lower opportunity cost payment. Baseline results found that the cost-minimizing decision for many biorefineries located in areas with higher opportunity cost land is to operate at a lower point along the participation rate function. A comparison of the Khanna et al. supply curve with the baseline supply curve in Figure 4.10 shows that the inclusion of participation rate functions dampens the estimated cost impact of biofuel expansion into areas with higher opportunity cost land.

Figure 4.10 – Estimated aggregate switchgrass ethanol supply from baseline model and assumptions used in previous literature[97]



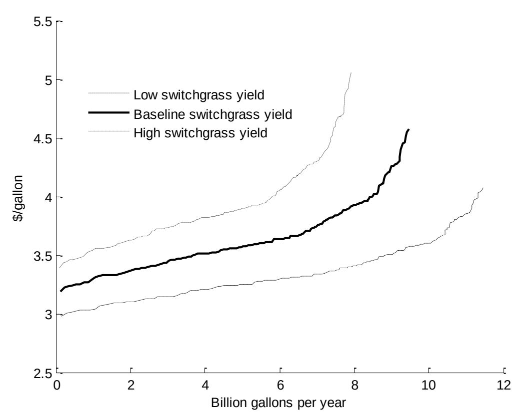
[97] Due to particularly high land opportunity costs, Figure 4.10 excludes the 5 highest cost biorefineries (CRDs) from the Khanna et al. (2011) scenario.

4.5.3 Sensitivity analysis

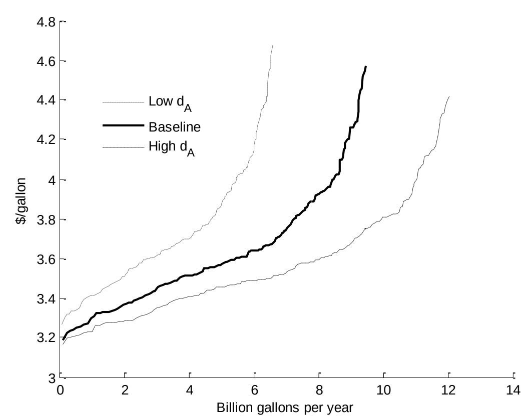
We evaluate the sensitivity of the baseline results to key model and parameter assumptions. Figure 4.11 indicates the sensitivity of the estimated supply curve to alternative model and parameter assumptions, and Appendix Table C.4.1 reports the average change in cost-minimizing biorefinery decisions. In all cases, more uncertainty exists at the upper end of the supply curve than the lower end of the supply curve. As biofuel production is expanded, greater opportunity exists to under- or over-estimate supply potential.

Figure 4.11 – Sensitivity of estimated ethanol supply to alternative model and parameter assumptions

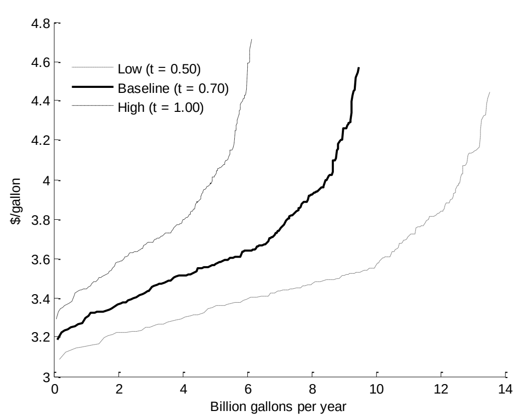
(a) Switchgrass yield (Y_B)



(b) Available biomass cropland (d_A)



(c) Variable transportation cost (*t*)



(d) Economies of scale

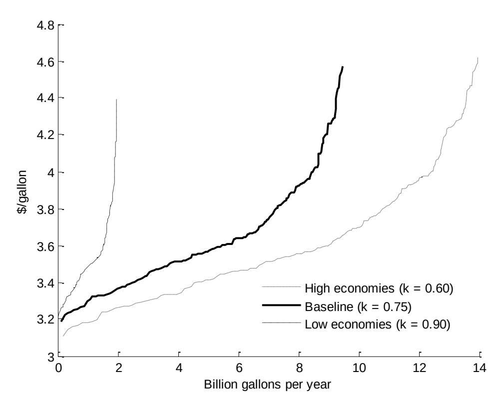
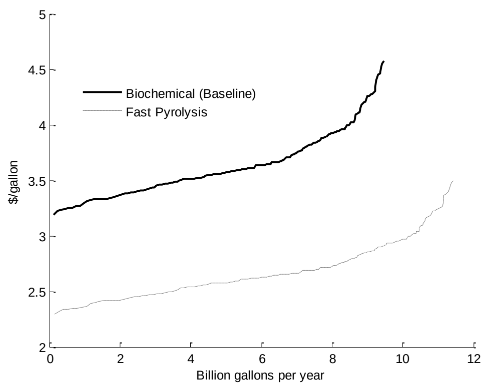
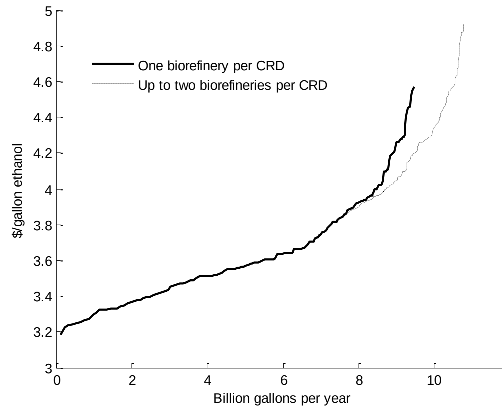


Figure 4.11 (continued)

(e) Fast Pyrolysis



(f) Two biorefineries per CRD



(g) Alternative transportation models

Switchgrass yield and production cost

The baseline results assume switchgrass yields at 75% of the values reported in Khanna et al. (2011). Consider two alternative yield percentages, 60% and 100%, denoted as the low and high yield assumptions.[98] The higher switchgrass yields result in lower cost biofuel production and larger total production (Figure 4.11a). The change in switchgrass yield does not have a uniform effect on all potential biorefinery locations. The difference in the estimated cost of biofuel production between yield assumptions increases with capacity. High cost producers face higher opportunity cost land and are more sensitive to a change in switchgrass yield.

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[98] Per dry ton switchgrass costs (P_{SG}) are adjusted appropriately.

Lower yields correspond to higher cost biofuel produced at smaller capacity biorefineries with slightly larger capture regions, lower participation rates, and higher land opportunity cost payments per dry ton (see Appendix Table C.4.1). Although the changes in the cost-minimizing production decisions are prevalent in all regions, the capacity effects are more pronounced for lower cost producers while the opportunity cost effects are more pronounced for higher cost producers.[99]

Land available for biomass production

Sensitivity to the amount of land available for biomass production (d_A) is evaluated using a high and low assumption. For high availability, the fraction of permanent pasture available for conversion is increased from 25% to 50% and harvested cropland from 10% to 25% as assumed in the Updated Billion Ton Report (U.S. DOE, 2011b). The low land availability assumes only 60% of landowners would consider supplying land for switchgrass production (i.e., $d_{A,low} = 0.60 * d_{A,base}$) based on survey findings summarized in Qualls et al. (2011) and Menard et al. (2011).[100] A change in available land for biomass production has comparable effects to the change in biomass yield (Figure 4.11b). Appendix C.5 considers the impact on model results from removing the upper bound on land available for switchgrass production in each region. Baseline model results are robust to removing this constraint given the range of land use elasticities reported in the literature.

Transportation cost

A decrease in the variable cost of transportation reduces diseconomies of transportation. To evaluate the impact of diseconomies of transportation, consider variable transportation costs per dry ton per mile of $0.50 and $1.00 from the baseline value of $0.71 per dry ton per mile. With lower transportation cost and therefore lower diseconomies of transportation, the cost-minimizing biorefinery is expected to increase capacity and/or decrease the land opportunity cost payment.

[99] Appendix Table C.4.2 provides the average difference in biorefinery characteristics between alternative assumptions and baseline results for the 10 least-cost locations identified by the baseline results.
[100] Based on a 2009 12-state survey, Qualls et al. (2011) and Menard et al. (2011) report only 60% of respondents were somewhat to very interested in supplying switchgrass for bioenergy even if "profitable."

Aggregate biofuel capacity increases (+ 4.1 bgy) and decreases (- 3.3 bgy) with the lower and higher transportation cost, respectively (Figure 4.11c). The capacity impacts are greater within the 10 least-cost locations (Appendix Table C.4.2). Although the change in the cost-minimizing participation rate was minimal on average, the standard deviation was approximately 2% across all CRDs and the percentage change ranged between -7% and +14% with the low transportation cost and -16% to +16% with the high transportation cost (Appendix Table C.4.1). This variation stems from locational differences in the economic trade-offs in switchgrass production, transportation, and conversion.

Economies of scale

While the variable cost of transportation determines the diseconomies of transportation, the economies of scale factor (k) determines the rate of biorefinery economies of scale. For k strictly less than one, the value $k-1$ represents the rate at which per gallon cost decreases with capacity, or the degree of economies of scale. The baseline results assume $k = 0.75$. Based on the values reported in the literature, we test the model results to a low and high k value: 0.60 and 0.90 (Cameron, Kumar, & Flynn, 2007; de Wit, Junginger, Lensink, Londo, & Faaij, 2010; Gan, 2007; Kaylen, Van Dyne, Choi, & Blase, 2000; Kumar, Cameron, & Flynn, 2003; Searcy & Flynn, 2009; Wright & Brown, 2007b). Biorefinery economies of scale are inversely related to k, and the cost-minimizing biorefinery capacity should be inversely related to k.

The supply curve is sensitive to economies of scale as shown in Figure 4.11d. The cost of biofuel production increases with lower economies of scale. Total biofuel production is 2 bgy, or a 7.5 bgy reduction from the baseline results. The average biorefinery decreases in capacity by 41 mgy with lower economies of scale. With high economies of scale, total production increases by 4.5 bgy to 14 bgy.

Biorefinery technology

The baseline biorefinery costs were taken from the biomass-to-ethanol biorefinery outlined in Kazi et al. (2010) using a biochemical conversion process. The biochemical conversion process was chosen for the baseline scenario since the engineering cost estimates for this process have been updated several times within the past 10 years (Aden, et al., 2002; Aden A. , 2009; Kazi, et al., 2010b; Aden A. , 2008).[101] Here we consider an alternative biomass to transportation fuel technology, fast pyrolysis. Wright et al. (2009; 2010) provide cost and technology estimates for a proposed 58.2 mgy biorefinery which converts biomass to bio-oil and subsequently upgrades bio-oil to naphtha and diesel range fuels.[102] Capital costs for the proposed biorefinery are $200 million or approximately $0.66 per gallon ($C_{P,Q_0}$) when amortized over a 20-year plant life at an interest rate of 8% and assuming a biofuel yield of 80 gallons per dry ton of switchgrass (Y_O). Total operating costs are approximately $0.72 per gallon ($C_{P,N}$).

The lower operating costs and capital costs for the fast pyrolysis conversion process result in lower cost biofuel and an increase in total production capacity (Figure 4.11e). Total production capacity increases by 2 bgy. On average, the cost and technology assumptions for fast pyrolysis conversion result in lower cost biofuel produced at larger capacity biorefineries (+11 mgy) with larger capture regions (Appendix Table C.4.1). The average impact on biorefinery capacity is greater within the 10 least cost per gallon locations (+24 mgy) (Appendix Table C.4.2).

Multiple biorefineries

For the results presented so far, the model is constrained to identify one biorefinery per CRD. Here we consider the impact on aggregate ethanol supply when districts have two biorefineries. First, none of the districts had enough area to support two cost-minimizing biorefineries side-by-side based on the capture region and area of the district. Therefore, the analysis considers a second biorefinery conditional on a first biorefinery already built with the cost-minimizing production conditions of

[101] The trend in the cost estimates has been an increase in the estimated (real) cost of biofuel production.
[102] The biorefinery outlined in Wright et al. (2009; 2010) is for a biorefinery converting corn stover to bio-oil with subsequent upgrading of the bio-oil to naphtha and diesel range fuels. As with the baseline model technology (biochemical), biorefinery costs are assumed to be similar for switchgrass and stover conversion with the same platform technology. Implications of this assumption were discussed in a footnote in section 4.4.2.

capacity, capture radius, and participation rate. The first biorefinery is assumed to have secured long-term contracts with landowners willing to supply land for biomass production at the offered price of biomass. The second biorefinery can contract with the remaining potential suppliers who were not willing to supply at the price offered by the first biorefinery, but are willing to supply at a higher price. In other words, the second biorefinery faces the remaining portion of the participation rate function [$d_S(P_{opp})$] above the participation rate captured by the first biorefinery. Given the first biorefinery in some CRDs contracted with almost 100% of available suppliers, a second biorefinery is not feasible in all locations. Locations are considered for a second biorefinery if they can support a capacity of at least 8 mgy.

Figure 4.11f compares the estimated aggregate ethanol supply curve with one biorefinery per CRD to the estimated supply curve with two potential biorefineries per CRD. The first location to have a second biorefinery enters the market at an ethanol price of $3.84 per gallon or at an aggregate production level of 7.5 bgy. Allowing two biorefineries per CRD increases the total production capacity to 10.8 bgy. Yet, the last 1 bgy of production is costly (> $4.30 per gallon ethanol or $6.45 per gallon gasoline equivalent). Given the first biorefinery has secured contracts for the least-cost biomass, a second biorefinery is unlikely to be economically feasible unless a new technology develops with significantly lower costs. Even in this situation, it may be more economical to retrofit or expand the existing biorefinery.

Alternative transportation models

Baseline results assume biomass is evenly distributed within the capture region and the biofuel processor cannot price discriminate between biomass suppliers. We consider two alternative approaches for modeling biomass transportation; one which allows for non-uniform participation within the capture region and a second which allows the biorefinery to price discriminate to capture transportation-related rents.

Based on a model of agricultural land use within an isolated state or final market, Von Thunen (1966) hypothesized a pattern of concentric rings of agricultural production that would reflect the cost of transportation to the final market. Here, the final market for biomass is the centrally-located biorefinery. Based on Von Thunen's model, biomass suppliers located closer to the biorefinery will benefit from location or bid rents. The baseline model accounts for such bid rents by assuming a biomass supplier located *x* miles from a biorefinery which contracts biomass from a capture radius *r* receives location-specific rents equal to $t * (r - x)$, where t is the variable transportation cost. Yet, the baseline model assumes biomass density is uniform within the capture region. The first alternative transportation model relaxes this assumption. For this alternative model, biomass suppliers located closer to the biorefinery are assumed to partially offset switchgrass production costs through higher location-specific rents. That is, the minimum biomass price required by landowner *i* located x_i miles from a biorefinery in district *j* to participate in switchgrass production will equal switchgrass production costs, including opportunity costs, less location-specific rents or

$$P_{SG,j} + \frac{P_{Opp,i,j}}{Y_{B,j}} + tr_j - tx_i. \tag{17}$$

Assuming the biorefinery offers all suppliers an equal price for biomass, the fraction of landowners willing to allocate land into biomass production at the offered biomass price will decrease with distance from the biorefinery. Therefore, the landowner participation rate in district *j* will not only vary with the price offered by the biorefinery to cover landowner opportunity cost ($P_{Opp,j}$) but also with the radius of the capture region (r_j) and distance from the biorefinery (x). The rate of landowner participation in district *j* at distance *x* can be written as follows:

$$d_j(P_{Opp,j}, r_j, x) = d_{A,j} * d_{S,j}\left(\frac{P_{Opp,j}}{Y_{B,j}} + tr_j - tx\right), \qquad \text{where} \quad \frac{\partial d_S}{\partial\left(\frac{P_{Opp,j}}{Y_{B,j}} + tr_j - tx\right)} \geq 0. \tag{18}$$

Incorporating this relationship between participation and hauling distance results in the following biorefinery objective function:

$$\min_{Q_j, P_{Opp,j}} C_j = \min_{Q, P_F} C_{P,N} + C_{P,Q_0} * \left[\frac{Q_j}{Q_0}\right]^{k-1} + \frac{1}{Y_O} * \left[P_{SG,j} + \frac{P_{Opp,j}}{Y_{B,j}} + S + t * r\right] \quad (19)$$

where
$$Q_j = Y_O * Y_{B_j} * 640 * d_{A_j} * \int_{x=0}^{r_j} 2\pi r_j \, d_{S,j}\left(P_{Opp,j} + tr_j - tx\right)dx \quad (19.1)$$

$$\frac{\partial d_{S,j}}{\partial(P_{Opp} + tr - tx)} \geq 0$$

$$d_{S,j}\left(P_{Opp,j} + tr_j - tx\right) \in [0, 1]$$

$$Q_j, P_{Opp,j} \geq 0.$$

Empirical estimation of constraint (19.1), which ensures biorefinery capacity is consistent with the amount of biomass supplied from the capture region, proceeds using the following step-wise approximation of the integral or a 'concentric ring' approach:

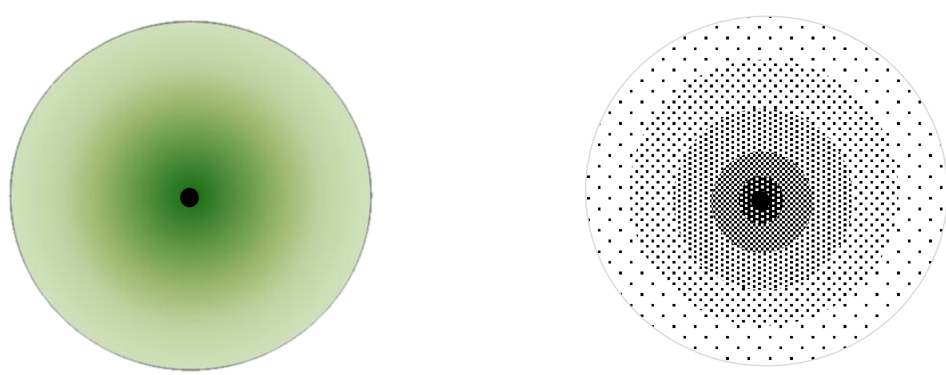
$$Q_j = Y_O * Y_{B,j} * d_{A,j} * 640 * \sum_{x=s}^{s \times r_j}\left[\pi x^2 d_{S,j}\left(P_{Opp,j} + r_j t - sxt\right) - \pi(x-s)^2 d_{S,j}\left(P_{Opp} + r_j t - sxt\right)\right]$$

$$= Y_O * Y_{B,j} * d_{A,j} * 640 * \pi * \sum_{x=s}^{s \times r_j}\left[(2xs - s^2) * d_{S,j}\left(P_{Opp,j} + r_j t - sxt\right)\right] \quad (20)$$

where s denotes the step size and assumed 0.5 mile in this application. Figure 4.12 provides a visual depiction of the theoretical and empirical approach to account for diminishing participation rate with distance from the biorefinery. The empirical approach for diminishing participation reflects Von Thunen's hypothesis of concentric rings that reflect the cost of transportation to the final market. The step size (s) in equation (20) represents the bandwidth of the concentric rings in Figure 4.12b.

Figure 4.12 – Theoretical and empirical approach to diminishing participation with distance from biorefinery

a. Theoretical approach **b. Empirical approach**



The second model considers the potential for a biorefinery to develop monopsony power in the local biomass market if biomass suppliers have limited options beyond the biorefinery. Since landowners are likely to anticipate this risk prior to allocating land into dedicated biomass production (Epplin, 2009), the monopsony power considered here is limited to transportation-related rents. The biorefinery is assumed to handle transportation and incur an average transportation cost equal to the product of the variable transportation cost (*t*) and average hauling distance within the capture region (*D*). The average hauling distance is derived using the equation from French (1960) for a circular capture area with a square road grid and uniform biomass density.[103] Compared to the baseline transportation model, any transportation-related rents (i.e., bid rents) from biomass located near the biorefinery are transferred from biomass suppliers to the processor.

Figure 4.11g provides estimated switchgrass ethanol supply curves under the alternative transportation models, and Appendix Table C.4.3 summarizes cost-minimizing biorefinery decisions. If the fixed transportation payment to biomass suppliers leads to higher participation near the biorefinery ('Diminishing participation' in figure 4.11g), per gallon production costs decrease by \$0.02 per gallon on average relative to the baseline model with uniform participation. On average, the participation rate of able land decreases from 99 percent next to the biorefinery to 70 percent at the capture region radius. A shift in transportation-related rents to the biorefinery ('Average hauling distance' in figure 4.11g) decreases per gallon biofuel costs at all quantity levels and increases cumulative production. The average biorefinery is larger (+10 bgy) and transports biomass from farther locations (+3 miles).

[103] The equation used to calculate the average hauling distance (*D*) is the same equation used to calculate the capture radius (equation 2) but with a different value for the parameter γ.With distance measured in miles and biomass yield measured per acre, γ for a circular area with a square road grid is 0.0189.

4.6 Conclusions

Cost efficient development of the cellulosic biofuel industry will not only require an understanding of the physical potential of biomass for alternative energy production as considered in several recent studies,[104] but also a better understanding of the location-specific production decisions and market arrangements to ensure sufficient feedstock supply and least-cost biofuel production (Bergtold, Fewell, & Williams, 2011; Rajagopal, Sexton, Roland-Holst, & Zilberman, 2007). While a complete examination of the necessary market conditions for commercial scale biofuel production fall outside the scope of this chapter, we took a closer look at the impact of spatial variation in biomass potential and land opportunity cost on potential supply of U.S. cellulosic biofuel.

A long-run biomass production through bioenergy conversion cost model was developed that incorporates heterogeneity of biomass suppliers within and between local markets. An application of the supply model to U.S. switchgrass-based ethanol production showed cost-minimizing production decisions – including biorefinery size, capture radius, and price of biomass – vary significantly across locations. Accounting for observed heterogeneity in potential biomass suppliers within and between local markets captured variation in the aggregate switchgrass ethanol supply curve not previously obtained. Empirical results confirm the hypothesis that economic trade-offs resulting from spatial variation in the economics of biomass production play an important role in the potential supply and distribution of U.S. cellulosic biofuel production.

We have gained insight into factors determining the economics of the cellulosic biofuel industry. The difference in the estimated quantity and cost of biofuel production with an endogenous versus fixed participation rate provides support for the value of identifying landowner willingness to move into biomass production. Further, the sensitivity of ethanol production costs to landowner willingness to consider biomass production suggests raising landowner awareness of the benefits

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[104]Gallagher, Dikeman, Fritz, Wailes, Gauthier, & Shapouri (2003), Graham, Nelson, Sheehan, Perlack, & Wright (2007), Perlack, Wright, Turhollow, Graham, Stokes, & Erback (2005), U.S. DOE (U.S. DOE, 2011b), and Walsh, de la Torre Ugarte, Shapouri, & Slinsk (2003).

from biomass production may be an important step in the feasibility of commercial scale production. The costs of ethanol production also were sensitive to the transportation cost, economies of scale factor, and biomass conversion technology. Development of ways to reduce variable transportation costs and decrease conversion costs will be critical in the economics of biofuel production.

We are currently extending the analysis to evaluate alternative feedstocks and multiple feedstock biorefineries. The results presented in this chapter are conditional on the data available for switchgrass production and biofuel processing. Since neither commercial scale biomass production nor biofuel processing has been realized, we rely on enterprise budgets and engineering cost estimates. Additional data from current pilot plants and future commercial scale operations will provide improved biomass production and biorefinery cost estimates. The unique dataset of CRP offers allows us to capture heterogeneity in landowner opportunity cost between and within markets. This is an underestimate of the potential heterogeneity within markets, but other sources of data are needed to explore farther. In future work we would like to extend the supply model to include additional sources of heterogeneity and price impacts from land use change to dedicated biomass production. Such extensions could provide further insight into the market impacts of cellulosic biofuel market development.

CHAPTER 5. GENERAL CONCLUSIONS

Since 1978, the U.S. government has provided financial support for the development and expansion of the biofuel industry. Although priorities shifted over time, the primary policy drivers include energy independence, rural development opportunities, and environmental benefits of biofuel relative to conventional fuel. Market conditions, including continuous ethanol subsidies between 1978 and 2011, led to rapid first-generation biofuel expansion between the early 1980s and late 2000s.

First-generation biofuel expansion slowed in recent years as high commodity prices, particularly during 2007 and 2008, squeezed profit margins. High commodity prices also generated criticism of first-generation biofuel for using food crops (e.g., corn, soybeans) as biofuel feedstocks. The so-called ‘food-versus-fuel’ debate created backlash against first-generation biofuel policies. Further, concerns arose about the potential of first-generation biofuel to significantly contribute to increased energy independence, provide rural development opportunities, and generate positive climate change impacts (Rosillo-Calle & Tschirley, 2010). For example, the entire 2010 U.S. corn crop converted to ethanol would only have provided gross energy equivalent to 24 days of U.S. crude oil use (Epplin & Haque, 2011).

First-generation biofuel concerns turned attention and interest to second-generation biofuel such as cellulosic biofuel. By using the structural material from plants rather than food crops, cellulosic biofuels avoid, or at least assuage, some of the issues faced by first-generation biofuels. Second-generation biofuels are also expected to be more water-efficient, require less arable land, and provide higher net energy balances and GHG emissions benefits (Schenk, et al., 2008; Wang, Wu, & Huo, 2007). The potential benefits of second-generation biofuel led to current policy support that includes market-based incentives and mandates. The 2008 Farm Bill provides tax credits to cellulosic biofuel producers and payment programs for biomass suppliers. The revised Renewable Fuel

Standard (RFS2) mandates use of increasing annual volumes of cellulosic biofuel between 2010 and 2022.

Despite government support, the cellulosic biofuel industry has been slow to develop. Each year since the RFS2 took effect, the EPA administrator has utilized a provision to waive a majority of the cellulosic biofuel mandate. The 2012 revised mandate is approximately 2% of the original mandate volume. The objectives of this dissertation are to provide a better understanding of why the cellulosic biofuel industry has been slow to develop and to identify important economic tradeoffs that will be encountered in commercial scale production.

An economic evaluation of local biofuel and biomass markets in Chapter 3 provided insights into why the cellulosic biofuel industry has been slow to develop. An application of the Biofuel Breakeven (BioBreak) program to 14 potential local cellulosic biofuel markets that vary by feedstock and location found biofuel production under baseline model assumptions (including no fiscal policy incentives and $100 per barrel oil) would result in expected losses between $0.82 and $1.65 per gallon ethanol ($1.23-2.48 per gallon gasoline equivalent, 2007$). Program results further suggest cellulosic ethanol production is not sustainable without significant policy intervention, or alternatively, unless long-run oil price exceeds $135 - $170 per barrel. The 2012 Annual Energy Outlook oil forecast for 2022 is $129 per barrel (2010$, reference scenario). At the 2035 oil price forecast of $145 per barrel, limited cellulosic biofuel production would be sustainable without policy support (U.S. EIA, 2012a).

One commonly mentioned justification for policy support is the potential environmental benefits of biofuel relative to conventional fuel. In particular, the RFS2 includes provisions that require biofuel in each subcategory (i.e., conventional, advanced, and cellulosic) to meet minimum GHG reduction standards. Chapter 3 provided an extension of the BioBreak results to evaluate the cost of reducing GHG emissions by substituting cellulosic ethanol for conventional fuel. Based on estimated prices and costs of biofuel production, policies that sustain cellulosic ethanol production would value a reduction in carbon equivalents between $141 and $280 per metric ton, higher than most carbon tax rates/prices or social costs of carbon discussed in the literature.

While a majority of previous literature has focused on either the feedstock supply system or biofuel refining process, the long-run breakeven models underlying BioBreak provide a complete accounting of all economic costs involved in biomass production, procurement, and conversion. As a result, the economic cost estimates of biofuel production identified by BioBreak are higher than frequently reported in other published studies. My estimates provide an indication of why the industry failed to develop and meet the RFS2 mandates for 2010, 2011, and 2012. Unless a more cost-efficient biomass production or biofuel conversion process is developed, long-run oil prices exceed existing forecasts, or existing biofuel policy become long-term, my results suggest industry development will likely remain limited in the near future.

While Chapter 3 provided a better understanding of the economic factors that have limited industry development, Chapter 4 provided a closer look at the economic trade-offs within the biorefinery industry and feedstock production processes. A long-run biomass production through bioenergy conversion cost model was developed to minimize costs of biomass feedstock acquisition and conversion in a potential biorefinery. A key aspect of the model is the treatment of local biomass supply. Previous literature has assumed the fraction of local landowners willing and able to participate in biomass supply is fixed and independent of the price of biomass. The model developed in Chapter 4 relaxed this assumption by incorporating location-specific supply relationships between biomass quantity and the price of biomass offered by the biorefinery (i.e., local biomass supply curves).

A theoretical model was specified and applied to switchgrass-based ethanol production within U.S. crop reporting districts (CRDs). In this application, local biomass supply curves were driven by variation in land opportunity costs. A dataset of offers submitted nationally for enrollment in the Conservation Reserve Program (CRP) was used to identify heterogeneity in opportunity cost of potential biomass cropland within each region. My empirical results indicate that incorporating location-specific biomass supply conditions creates unique and important economic tradeoffs within each CRD. The cost-minimizing biorefinery production conditions, including capacity, vary significantly across locations. These differences have important impacts on the potential supply and distribution of U.S. cellulosic biofuel production. Accounting for observed heterogeneity in land opportunity costs captured variation in the aggregate switchgrass ethanol supply curve not otherwise obtained.

Several implications arise from these results. First, ignoring local trade-offs in biomass procurement may lead to a significant under- or over-estimate of the quantity and cost of U.S. cellulosic biofuel production. If incorporated into models used to simulate bio-energy policy shocks, the economic welfare impacts from cellulosic biofuel policies may be seriously distorted. Further, biased cost estimates may distort the relative attractiveness of cellulosic biofuel to competing energy technologies such as hydrogen, oil shale-derived fuels, tar sands-derived fuels, coal-to-liquids, and electricity. Second, sensitivity of biofuel production costs to landowner willingness to consider biomass production suggests raising landowner awareness of the benefits from biomass production may be an important step in the feasibility of commercial scale production. Finally, the costs of ethanol production were found to be sensitive to transportation cost, conversion plant economies of scale, and biomass conversion technology.

The chapters within this dissertation, although each written as a stand-alone paper, contribute to a growing body of literature on the economics of second generation biofuel and provide insight into important economic trade-offs that will be encountered in the development of a U.S. cellulosic biofuel industry.

APPENDIX A. ADDITIONAL MATERIAL FOR CHAPTER 2

Appendix A.1 – Timeline of federal ethanol policies and major events

Year	Policy/Event
1862	Union Congress imposed a $2.08 per gallon tax on ethanol to fund Civil War[105]
1906	Tax on ethanol removed
1919	***18th Amendment to the U.S. Constitution*** • Prohibition
1973	Arab oil embargo leads to the 1973 Oil Crisis
1973	EPA announces phase-out of lead in all grades of gasoline
1978	***Energy Tax Act of 1978*** • Excise tax exemption for ethanol equivalent to 40 cents per gallon blended ethanol
1979	Events surrounding the Iranian Revolution lead to a second energy crisis
1980	Import tariff imposed on foreign-produced biofuels ***1980 Energy Security Act*** (ESA) • Official definition for gasohol • Price guarantees for biomass energy projects and loan guarantees to small ethanol producers ***Gasohol Competition Act*** • Prohibited discrimination against sale of gasohol ***Crude Oil Windfall Profit Tax Act*** • Extended excise tax credit equivalent to $0.40 per gallon ethanol
1982	***Surface Transportation Assistance Act*** • Increased excise tax credit to $0.50 per gallon ethanol
1984	***Tax Reform Act*** • Increased excise tax credit to $0.60 per gallon ethanol
1988	***Alternative Motor Fuels Act*** (AMFA) • CAFE credits provided to manufacturers of flexible fuel vehicles
1990	***Omnibus Budget Reconciliation Act of 1990*** • Reduced excise tax credit to $0.54 per gallon ethanol • Additional $0.10 per gallon tax credit for small producers (less than 30 mgy) ***Clean Air Act Amendments*** (CAAA) • Required oxygenated fuel use in certain areas during winter months
1992	***Energy Policy Act*** (EPAct 1992) • Defined fuel types that qualified as alternative fuels • Tax deductions for vehicles purchased or converted to operate on alternative fuels • Required federal and state vehicle fleets to contain 75% alternative fuel vehicles
1998	***Transportation Efficiency Act of the 21st Century*** (TEA-21) • Extended ethanol tax credit through 2007 with gradual reductions from $0.54 to $0.51 cents by 2005
2000	EPA recommends national phase-out of MTBE
2001	Ethanol tax credit reduced to $0.53 per gallon in agreement with TEA-21
2003	Ethanol tax credit reduced to $0.52 per gallon in agreement with TEA-21
2004	***Job Creation Act*** • Ethanol excise tax credit modified into a blender's tax credit termed the Volumetric Ethanol Excise Tax Credit (VEETC) • VEETC extended to 2010

[105] The alcohol tax passed by the Union Congress was intended as a tax on consumption alcohol. Since no exemptions were extended, the tax also applied to fuel ethanol.

Appendix A.1 continued

2005	VEETC reduced to $0.51 per gallon in agreement with TEA-21 ***EPAct 2005*** • Eliminated oxygenate fuel requirement from 1990 CAAA • Introduced Renewable Fuels Standard (RFS) which required increasing volumes of renewable fuel use up to 7.5 bgy in 2012 • Modified definition of "small ethanol producer" from 30 to 60 mgy
2007	***Energy Independence and Security Act*** (EISA) • Introduced Revised Renewable Fuels Standard (RFS2) with higher annual volumes of renewable fuel use that increase up to 36 bgy in 2022 • GHG reduction standards for each biofuel subcategory
2008	***Food, Conservation, and Energy Act of 2008*** (2008 Farm Bill) • Funded several programs for renewable energy, biobased products, and bioenergy • Reduced VEETC to $0.45 per gallon starting in 2009 • Established cellulosic biofuel producer tax credit of $1.01 per gallon • Biomass Crop Assistance Program (BCAP)
2009	***American Reinvestment and Recovery Act*** (Recovery Act) • Funded bioenergy research projects including development of pilot, demonstration, and commercial-scale biorefineries
2011	Senate voted to repeal the tax credit and tariff for conventional ethanol (June 16) • Tax credit and tariff expired on December 31

Appendix A.2 – Biomass-to-ethanol production processes for lignocellulosic feedstocks

Several methods exist to convert biorenewable resources into biofuel. Multiple methods are necessary for the different types of biorenewable resources which can be converted into ethanol (see Section 2.5). The different types of biomass can be broken into three main categories: sugar crops, starch based crops, and lignocellulosic feedstocks. Sugar crops have shown to be an economical source for fuel transportation in Brazil but have not developed in the United States due to sugar subsidies (Brown, 2003). Currently, the United States ethanol industry is based on starch-based feedstocks (ex: corn). This section will describe the different processes available for lignocellulosic ethanol production.

Lignocellulosic biomass is composed of three materials: cellulose, hemicellulose, and lignin. Cellulose and hemicellulose can be converted into ethanol, while lignin is a byproduct of the ethanol production process which can be burned to generate electricity in certain processes used. Corn residues contain approximately 38%, 32% and 17% of cellulose, hemicellulose, and lignin, respectively (Kaylen M. , Van Dyne, Choi, & Blase, 2000). Table A.2.1 provides the composition for other potential biofuel feedstocks.

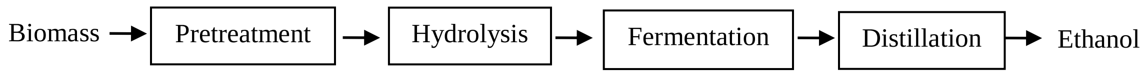
Table A.2.1 – Cellulose, hemicellulose, and lignin content in potential biofuel feedstocks

Agricultural residue	Cellulose	Hemicellulose	Lignin
Hardwood stem	40-50	24-40	18-25
Softwood stem	45-50	25-35	25-35
Corn cobs	45	35	15
Grasses	25-40	35-50	10-30
Wheat straw	33-40	20-25	15-20
Rice straw	40	18	5.5
Leaves	15-20	80-85	0
Cotton seed hairs	60	20	20
Switchgrass	30-50	10-40	5-20
Paper	85-99	0	0-15

Source: Prasad et al., (2007) *Table 4, page 6*

The conversion of lignocellulosic feedstocks into ethanol consists of four main steps: pretreatment, hydrolysis, fermentation, and distillation (Figure A.2.1).

Figure A.2.1- Biomass-to-ethanol conversion process



Pretreatment

Pretreatment is used to increase the efficiency of subsequent stages of production. There are four main goals in pretreatment (Sun & Cheng, 2002, p. 2):

> " 1) improve the formation of sugars or the ability to subsequently form sugars by enzymatic hydrolysis;
>
> 2) avoid the degradation or loss of carbohydrate;
>
> 3) avoid the formation of byproducts inhibitory to the subsequent hydrolysis and fermentation processes; and
>
> 4) be cost effective."

Utilizing a cost-effective pretreatment process is essential – pretreatment costs are approximately 1/3 of total processing costs. During pretreatment, the feedstock is sized, typically using hammer mills. The process of size reduction, called comminution, increases the surface area of the material in order to become more susceptible to hydrolysis (Brown, 2003).

The extensiveness and method of pretreatment will depend on the subsequent hydrolysis method. Described in more detail in the following section, there are two main categories of hydrolysis: acid-based and enzymatic hydrolysis. Preliminary comminution is sufficient for acid hydrolysis, but to increase yield, some additional pretreatment is typically employed. Additional pretreatment is necessary for enzymatic hydrolysis. Sugar yields are only 20% with initial sizing and increase to over 90% with additional pretreatment methods (Brown, 2003). There are several pretreatment methods, each with advantages and disadvantages. Categories for pretreatment methods include: biological, alkaline, steam explosion, pre-hydrolysis, ammonia fiber explosion, and treatment with organic solvents. Each of these pretreatment methods is considered in the following subsections.

Biological

Biological pretreatments use microorganisms that decompose the lignin from the lignocellulosic matter. This allows the cellulose and hemicellulose to release (Brown, 2003). The biological pre-treatment process currently available utilizes fungi. Yet, the low hydrolysis rate of fungi pre-treatment may offset the benefits of low energy use and lack of environmental concerns (Hamelinck, van Hooijdonk, & Faaij, 2005). Other disadvantages include the long reaction time and lower yields if organisms grow on the resulting sugars. Overall, biological pretreatments are not fully developed (Brown, 2003).

Alkaline

Alkaline pretreatment dissolves lignin and hemicelluloses and can potentially swell cellulose (Brown, 2003). Typical alkaline pretreatment utilizes a base such as sodium hydroxide or calcium hydroxide (Hamelinck, van Hooijdonk, & Faaij, 2005). Even with the benefits of dissolving lignin, the destroyed hemicellulose is a significant loss in fermentable sugar. Another major disadvantage of this process is the amount of chemicals consumed to neutralize the acidic carboxylic groups in the biomass (Brown, 2003).

Steam Explosion

Steam explosion uses high-pressure steam to penetrate the pores of the plant material followed by rapid decompression. The explosive expansion increases the accessibility during hydrolysis (Brown, 2003). This is one of the more promising pretreatment methods but developments are needed to increase yield and decrease costs (Hamelinck, van Hooijdonk, & Faaij, 2005).

Pre-hydrolysis

Pre-hydrolysis is characterized by the addition of small amounts of mineral acids. The most common mineral acid used in pre-hydrolysis is sulfuric acid. The biomass is treated with the mineral acid and incubated for approximately 30 minutes. This pretreatment method improves the hydrolysis of hemicellulose at lower temperatures and increases the enzymatic digestibility of the cellulose as high as 90%. An alternative option is sulfur dioxide, which is less corrosive than sulfuric acid. One advantage of this pretreatment method is the byproduct furfural. Furfural has value in both the oil refining market as a solvent and the carpet industry. The disadvantages include the need to neutralize the acidified biomass and the possibility of sugar decomposition. Pre-hydrolysis is also commonly referred to as: dilute acid pretreatment or acid-catalyzed steam explosion (Brown, 2003).

Ammonia Fiber Explosion (AFEX)

AFEX uses a similar process to steam explosion but utilizes liquid ammonia. The mixture is incubated for several minutes to an hour, which allows the ammonia to penetrate. Hydrolysis yields range from 80-90% of theoretical. One disadvantage is that AFEX has not been successful for either hardwoods or softwoods (Brown, 2003).

Organic Solvents

Organic solvents are used to remove lignin from biomass. Removal of lignin can decrease the requirement of costly enzymes in subsequent processing, specifically enzymatic hydrolysis. Lignin that is not removed will absorb significant amounts of enzymes and inhibit the efficiency of hydrolysis. Organic solvents are sometimes used in conjunction with acidic or alkaline pretreatment methods (Brown, 2003).

Hydrolysis

The second step in the biomass-to-ethanol process is hydrolysis. During hydrolysis, the cellulose portion of the biomass is converted into sugar. The three methods for hydrolysis include: concentrated acid, dilute acid, and enzymatic. As noted earlier, acidic methods do not need extra pretreatment but enzymatic hydrolysis must be preceded with extensive pretreatment to separate the lignin, hemicellulose, and cellulose (Brown, 2003).

Concentrated-acid

The concentrated-acid hydrolysis method is relative simple and produces sugar yields which approach 100% of theoretical. In order to ferment, the solution is diluted and heated to a boiling point for four hours. The solution is then neutralized with limestone and allowed to ferment. The two acids available at a commercial level are sulfuric acid and hydrochloric acid. The benefit of sulfuric acid is the low cost compared to hydrochloric acid. Yet, the disadvantages include the large volume requirement and the complicated recovery process due to its high boiling point. Hydrochloric acid, though more expensive and corrosive, has a higher volatility which presents better recovery opportunities during distillation (Brown, 2003).

Dilute-acid

Dilute-acid hydrolysis uses significantly less acid to hydrolyze the lignocellulosic matter than concentrated-acid hydrolysis. Dilute-acid hydrolysis is accelerated by operating at higher temperatures, but this causes the decomposition of oligosaccharides released from the lignocellulose, ultimately reducing yields to only 55-60% of theoretical. Another disadvantage of this process is the large number of microbial toxins that are produced, such as acetic acid and furfural, which can inhibit fermentation of sugars. Dilute-acid hydrolysis also needs corrosion-resistant equipment which increases production costs (Brown, 2003).

Enzymatic

Enzymatic hydrolysis was initially developed to capture a higher percentage of the cellulose and hemicellulose components. The cellulosic bonds are broken apart by a mixture of enzymes called cellulase (Brown, 2003). Hamelinck et al. (2005, p. 392) described cellulase as a “complex mix of enzymes that work together synergistically to attack typical parts of the cellulose fibre.” Depending on the composition of the matter, hemicellulase might also be used to break down any hemicellulose left over from the pretreatment process. Disadvantages include relatively low specific activity which leads to high enzyme requirements and slow rates of conversion (Brown, 2003).

Fermentation

Fermentation follows hydrolysis. Fermentation is defined as a biological process in which enzymes produced by microorganisms catalyze energy-releasing reactions that break down complex organic substrates (Brown, 2003). The first step in fermentation is the detoxification of the hydrolysate. During detoxification, toxic compounds such as furfural and acetic acid that would inhibit the growth of fermentation organisms are removed. There are many yeast species and a few bacteria that can efficiently ferment six-carbon sugars such as corn starch to ethanol, but lignocellulosic matter has five-carbon sugars, which require a more complex fermentation process. There have been 3 approaches developed for fermenting lignocellulosic sugars: separate hydrolysis fermentation (SHF), simultaneous saccharification and fermentation (SSF), and direct microbial conversion (DMC) (Brown, 2003).

Separate Hydrolysis Fermentation (SHF)

Separate hydrolysis fermentation (SHF) separates pre-hydrolysis, enzymatic hydrolysis, and fermentation. This separation helps to avoid undesirable interactions during the different steps. One major disadvantage to this method is that it requires lower solids loadings in order to obtain reasonable yields (Brown, 2003).

Simultaneous Saccharification and Fermentation (SSF)

Simultaneous saccharification and fermentation (SSF) combines hydrolysis and fermentation. By combining these two stages, glucose is rapidly removed before it can inhibit further hydrolysis. During SSF, the biomass feedstock is first milled and then pre-hydrolyzed. The mixture from pre-hydrolysis is then neutralized with limestone. It is then mixed with enzymes, hemicellulose, and cellulase along with yeast and nutrients. The cellulose and remaining hemicellulose are solubilized and fermented into ethanol. During this process, the lignin is separated and used as a boiler fuel (Brown, 2003).

Direct Microbial Conversion (DMC)

Direct microbial conversion (DMC) combines cellulase production, cellulose hydrolysis, and glucose fermentation into one step. The advantages of DMC are the low number of reactors, the simple operation, and the reduction of chemical costs. The disadvantages include the low product yield, undesirable metabolic by-products, and product inhibition. This process needs future development in order to become economically viable (Brown, 2003).

Distillation

The last step in conversion of lignocellulosic matter to ethanol is distillation. Fermentation may generate gas, precipitate, and/or water-soluble compounds. The gaseous or precipitated products can easily be separated from the “beer.” The water-soluble compounds that are not easily separated from the beer are recovered through the distillation process. Distillation is an energy-intensive process completed in multiple phases. The first distillation yields ethanol (55%) and stillage bottoms. These stillage bottoms are marketable as animal feed, also known as distillers grains and solubles. The second distillation yields ethanol (95-96%) and water azeotrope. Some production processes stop at this point. If water-free ethanol is desired, the liquid can be purified using several different methods including further distillation. Criticisms that ethanol consumes more energy than it produces stem mostly from the distillation process which is an energy-intensive operation. Yet, recent technology has reduced these concerns (Brown, 2003).

APPENDIX B. ADDITIONAL MATERIAL FOR CHAPTER 3

Appendix B.1 – Summary of BioBreak application parameter assumptions

Summary of parameter assumptions for processor derived demand (*DD*)

Price of oil **(P_{oil})**

A critical parameter of the processor's breakeven price is the price of oil. Based on Cushing Crude Spot Prices (2010), oil escalated to $145 per barrel in July 2009 but dropped to $30 per barrel by the end of 2008. The price increased to $48 per barrel the first week of 2009 and ended 2010 at $90. Given the high volatility in crude oil spot prices, rather than simulating or specifying a single price for oil, this analysis considers three oil price levels: $50, $100, and $150 per barrel.

Energy equivalent factor **(E_V)** ***and octane value*** **(V_O)**

Per unit, ethanol provides a lower energy value than gasoline. The energy equivalent ratio (E_V) for ethanol to gasoline is assumed fixed at 0.667.[106] While it has a lower energy value than pure gasoline, ethanol is an octane enhancer. Blending gasoline with ethanol, even at low levels, will increase the fuel's octane value. For simplicity, the octane enhancement value (V_O) is fixed at $0.10 per gallon.

Co-product value **(V_C)**

For co-product value (V_C), this analysis assumes excess energy is the only co-product from the proposed biorefinery. Aden et al. (2002) estimated corn stover cellulosic ethanol production yields excess energy value of approximately $0.14-$0.21, after updating to 2007 energy costs (U.S. EIA, 2008). Without specifying the source of co-product value, Khanna & Dhungana (2007) used an estimate of around $0.16 per gallon for cellulosic ethanol.[107] Huang et al. (2009) found switchgrass conversion yields the largest amount of excess electricity followed by corn stover and aspen wood. Assuming current technology and 2007 costs, Kazi et al. (2010b) estimate a stover biochemical plant will produce 4.06 kWh of excess electricity per gallon corresponding to a co-product value of $0.22 per gallon. Corn stover ethanol is assumed to have a fixed co-product value of $0.22 per gallon, while switchgrass, *Miscanthus*, wheat straw, and alfalfa have a value of $0.24 per gallon and woody biomass has a value of $0.20 per gallon.

[106] Elobeid, Tokogz, Hayes, Babcock, & Hart (2006); Tokgoz et al. (2007)
[107] Updated to 2007 costs

***Conversion ratio* (Y_O)**

The conversion ratio of ethanol from biomass (Y_O) is expected to vary based on feedstock type (i.e. cellulose, hemicellulose, and lignin content), conversion process, and biorefinery efficiency. Research estimates for the conversion ratio have ranged from as low as 55 gallons per ton to theoretical values as high as 140 gallons per ton.[108] Eliminating theoretical values and outliers on either end, the reported range for the conversion ratio is approximately 65-100 gallons per dry ton. Based on the large variation within the research estimates, a conversion ratio with a mean value of 70 gallons per ton is assumed to be representative of current and near future technology.[109] A conversion rate of 70 gallons per ton for near-term technology is consistent with the value estimated by Kazi et al. (2010b) for stover cellulosic ethanol production by fermentation in the next 5-8 years. An increase in the long-run conversion ratio to 80 gallons per ton is considered within the sensitivity analysis.

***Biorefinery investment costs* (C_I)**

Investment or capital costs for a biorefinery have been estimated to be four to five times higher than starch-based ethanol plants of similar size (Wright & Brown, 2007). The biorefinery cost estimates used in this model are based on research estimates and costs provided by Kazi et al. (2010b) for a 53.4 million gallon per year corn stover ethanol refinery utilizing dilute acid prehydrolysis with saccharification and cofermentation. Cost estimates were based on a biorefinery with a 20 year life span that processes 2,205 tons of corn stover per day and operates 350 days per day at a conversion rate of 69.5 gallons of ethanol per ton of stover. The biorefinery is assumed to outsource stover harvest, delivery, and long-term storage. Investment costs include on-site storage infrastructure capable of handling up to 72 hours of corn stover supply. Given these assumptions, the total capital costs for the biorefinery outline by Kazi et al. (2010b) were $375.9 million (2007$). We assume no down payments and amortize the investment cost over 20 years at 10% to derive an investment cost of $0.82 per gallon. Assuming no down payments and an interest rate of 10%, we do not explicitly

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[108] Aden et al. (2002); Atchison & Hettenhaus (2003); BRDI (2008); Chen, Huang, Khanna, & Onal (2010); Comis (2006); Crooks (2006); Huang, Ramaswamy, Al-Dajani, Tschirner, & Cairncross (2009); Kazi et al. (2010a); Khanna (2008); Khanna & Dhungana (2007); Krissek (2008); McAloon, Taylor, Yee, Ibsen, & Wooley (2000); Perlack & Turhollow (2002); Petrolia (2008); Tiffany, Jordan, Dietrich, & Vargo-Daggett (2006); Tokgoz et al. (2007)

[109] Ethanol yields vary by feedstock but we were unable to find consistent yield patterns across studies, especially given the lack of commercial cellulosic ethanol plant yield information. Even though woody biomass has a higher lignin yield, some studies also assign a relatively high ethanol yield. With a wide range of estimates for both herbaceous crops and woody biomass and the lack of commercial yield estimates, we chose a conservative approach by assuming the same yield for all feedstock, similar to the ALTF Report (2009). The model has been estimated with varying ethanol yield by feedstock and results are available upon request.

include deprecation costs or minimum average return on investment. For this analysis, biorefinery capital investment costs are assumed to follow a normal distribution with a mean value of $0.82 per gallon.

***Operating costs* (C_O)**

Operating costs are separated into two components: enzyme costs and non-enzyme operating costs. Non-enzyme operating costs, including salaries, overhead, maintenance, insurance, taxes, and other conversion costs, are fixed at $0.92 per gallon based on the cost estimates provided in Kazi et al. (2010b).[110] Discussions with industry sources indicate enzyme costs may run between $0.40 and $1.00 per gallon given current yields and technology. The decrease in enzyme costs to $0.10 per gallon anticipated by Aden et al. (2002) has not materialized. To be consistent with the biorefinery used for non-operating and investment costs, the enzyme cost from Kazi et al. (2010b) of $0.70 per gallon are used for the mean value in this analysis.

***Government incentives* (G_P)**

Growing concern over climate change as well as energy security and independence has resulted in various incentives and mandates for renewable fuels. Tax credits have been the primary financial incentive provided to biofuel producers. To account for potential tax credits for cellulosic ethanol producers, sensitivity analysis considers the current tax credit for cellulosic ethanol producers designated by the Food and Energy Security Act of 2007 of $1.01 per gallon and denote this as the "producer's tax credit."

Summary of parameter assumptions for biomass supply cost (*SC*)

***Nutrient replacement* (C_{NR})**

Uncollected cellulosic material adds value to the soil through protection against rain, wind, and radiation, therefore limiting erosion. Biomass suppliers will incorporate the costs of soil damage and nutrient loss from biomass collection into the minimum price they are willing to accept. Nutrient replacement cost (C_{NR}) varies by feedstock and harvest technique. After adjusting for 2007 costs,[111]

[110] The operating cost used in this analysis is derived from the operating costs presented in Appendix Table D-1 in Kazi et al. (2010a) excluding feedstock, cellulose, depreciation, and return on investment costs and electricity credits.
[111] Nutrient and replacement costs were updated using USDA NASS Agricultural Fertilizer Prices from 1999-2007 (NASS, 2007a; 2007b).

estimates for nutrient replacement costs range from \$5 to \$21 per ton.[112] Given the research estimates, nutrient replacement is assumed to have a mean (likeliest) value of \$13.60 (\$14.60) per ton for stover, \$15.60 (\$16.60) per ton for switchgrass, \$8.35 per ton for *Miscanthus*,[113] and \$5.6 per ton for wheat straw. Alfalfa is assumed to have a two year stand with first-year nutrient costs incorporated into the establishment costs discussed below and a cost of \$62.50 per acre for second year nutrient application. Given the yield assumptions, \$60 per acre corresponds to approximately \$15.60 per ton for second year alfalfa. Nutrient replacement is assumed unnecessary for woody biomass.

***Harvest and maintenance costs* (C_{HM}) *and stumpage fees* (*SF*)**

Harvest and maintenance cost (C_{HM}) estimates for cellulosic material have varied based on harvest technique and feedstock. Non-custom harvest research estimates range from \$14 to \$84 per ton for corn stover,[114] \$16 to \$58 per ton for switchgrass[115] and \$19 to \$54 per ton for *Miscanthus*,[116] after adjusting for 2007 costs.[117] Estimates for non-specific biomass range between \$15 and \$38 per ton.[118] Woody biomass collection costs up to roadside range between \$17 and \$50 per ton.[119] Spelter & Toth (2009) find total delivered costs (including transportation) around \$58, \$66, \$75, and \$86 per dry ton[120] for woody residue in the Northeast, South, North, and West regions, respectively.

Using the timber harvesting cost simulator outlined in Fight, Hartsough, & Noordijk (2006), Sohngen, Anderson, Petrova, & Goslee (2010) found harvest costs up to roadside around \$25 per dry ton, with a high cost scenario of \$34 per dry ton. For simulation, harvest and maintenance costs are

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[112] Aden et al. (2002); Atchison & Hettenhaus (2003); Brechbill & Tyner (2008a); Hoskinson, Karlin, Birrell, Radtke, & Wilhelm (2007); Huang et al. (2009); Karlen (2010); Karlen & Birrell (Presentation); Khanna & Dhungana (2007); Khanna, Dhungana, & Clifton-Brown (2008); Perlack & Turhollow (2003); Perrin, Vogel, Schmer, & Mitchell (2008); Petrolia (2008)
[113] The nutrient replacement cost for *Miscanthus* is based on the recommended fertilizer replacement rates summarized in Khanna, Dhungana, & Clifton-Brown (2008). The mean value used in simulation was derived using the average fertilizer rates and costs (updated to 2007) reported by Khanna, Dhungana, & Clifton-Brown (2008).
[114] Aden et al. (2002); Brechbill & Tyner (2008a); Edwards (2007); Hess, Wright, & Kenney (2007); Huang et al. (2009); Khanna (2008); McAloon, Taylor, Yee, Ibsen, & Wooley (2000); Perlack (2007, Presentation); Sokhansanj & Turhollow (2002); Suzuki (2006)
[115] Brechbill & Tyner (2008a); Duffy (2007); Huang et al. (2009); Khanna (2008); Khanna & Dhungana (2007); Khanna, Dhungana, & Clifton-Brown (2008); Kumar & Sokhansanj (2007); Perrin et al. (2008); Tiffany et al. (2006)
[116] Khanna (2008); Khanna & Dhungana (2007); Khanna, Dhungana, & Clifton-Brown (2008)
[117] Harvest and maintenance costs were updated using USDA NASS Agricultural fuel, machinery and labor prices from 1999-2007 (NASS, 2007a; 2007b).
[118] Mapemba, Epplin, Taliaferro, & Huhnke (2007); Mapemba, Epplin, Huhnke, & Taliaferro (2008)
[119] BRDI (2008); Jenkins et al. (2009); Sohngen, Anderson, Petrova, & Goslee (2010); USDA Forest Service (2003; 2005)
[120] Based on a conversion rate of 0.59 dry tons per green tons.

assumed to have mean (likeliest) values of $43 ($46), $36 ($38), $45 ($48), $31.5 ($33), and $26 for stover, switchgrass, *Miscanthus,* wheat straw, and woody biomass, respectively. Alfalfa is assumed to be harvested once during the first year and three times during the second year at a cost of $55 per acre per harvest. In addition to harvest costs, farmed tree suppliers incur a stumpage fee (SF) with an assumed mean value of $20 per ton.

***Transportation costs* (*t*, *DFC*, and *D*)**

Previous research on transportation of biomass has provided two distinct types of cost estimates: (1) total transportation cost; and (2) breakdown of variable and fixed transportation costs. Research estimates for total corn stover transportation costs range between $3 per ton and $32 per ton.[121] Total switchgrass and *Miscanthus* transportation costs have been estimated between $14 and $36 per ton,[122] adjusted to 2007 costs.[123] Woody biomass transportation costs are expected to range between $11 and $30 per dry ton.[124] Based on the second method, distance variable cost (*t*) estimates range between $0.09 and $0.60 per ton per mile,[125] while distance fixed cost (*DFC*) estimates range between $4.80 and $9.80 per ton, [126] depending on feedstock type. BioBreak utilizes the latter method of separating fixed and variable transportation costs.

The *DFC* for corn stover, switchgrass, *Miscanthus,* wheat straw, and second year alfalfa is assumed to range from $5 to $12 per ton with a mean value of $8.50 per ton. Besides loading and unloading costs, woody biomass requires an on-site chipping fee. Therefore, the DFC for woody biomass is assumed to have a mean value of $10 per ton. Distance variable cost (*t*) is assumed to follow a skewed distribution to account for future technological progress in transportation of biomass with a mean (likeliest) value of $0.35 ($0.38) per ton per mile for stover, switchgrass, *Miscanthus*, wheat straw, and second year alfalfa and $0.50 (0.53) per ton per mile for woody biomass.

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[121] Aden et al. (2002); Atchison & Hettenhaus (2003); Brechbill & Tyner (2008a), English et al. (2006); Hess, Wright, & Kenney (2007); Mapemba et al. (2008); Perlack (2007, Presentation); Perlack & Turhollow (2002); Vadas, Barnett, & Undersander (2008)

[122] Brechbill & Tyner (2008a); Duffy (2007); Khanna, Dhungana, & Clifton-Brown (2008); Kumar & Sokhansanj (2007); Mapemba et al. (2007); Mapemba et al. (2008); Perrin et al. (2008); Tiffany et al. (2006); Vadas et al. (2008)

[123] Transportation costs were updated using USDA NASS Agricultural fuel prices from 1999-2007 (NASS, 2007a; 2007b).

[124] Sohngen et al. (2010); Summit Ridge Investments (2007)

[125] Brechbill & Tyner (2008a); Huang et al. (2009); Jenkins et al. (2009); Kaylen, Van Dyne, Choi, & Blasé (2000); Kumar, Cameron, & Flynn (2003; 2005); Petrolia (2008); Searcy, Flynn, Ghafoori, & Kumar (2007); Sohngen et al. (2010); USDA Forest Service (2003; 2005)

[126] Huang et al. (2009); Kumar, Cameron, & Flynn (2003; 2005); Petrolia (2008); Searcy, Flynn, Ghafoori, & Kumar (2007)

One-way transportation distance (D) has been evaluated up to 140 miles for woody biomass[127] and between 5 and 75 miles[128] for all other feedstocks. In the BioBreak program, the average hauling distance is calculated using the formulation by French (1960) for a circular supply area with a square road grid provided in the equation below. Average distance (D) is a function of the annual biorefinery biomass demand (Q), annual biomass yield (Y_B), and biomass density (d).

$$D = 0.4789\sqrt{\frac{Q}{640 * Y_B * d}}$$

Annual biomass demand is assumed to be consistent with the biorefinery outlined for capital and operating cost distributions (771,750 tons per year). Biomass density is assumed to follow a normal distribution with a mean value of 0.20 for all feedstocks with the exception of alfalfa which has a biomass density of 0.15.[129,130]

Storage costs (C_S)

Due to the low density of biomass compared to traditional cash crops such as corn and soybeans, biomass storage costs (C_S) can vary greatly depending on the feedstock type, harvest technique, and type of storage area. Adjusted for 2007 costs, biomass storage estimates range between $2 and $23 per ton.[131, 132] For simulation, storage costs are assumed to follow a skewed distribution for all feedstocks to allow for advancement in storage and densification techniques. The mean (likeliest) cost for woody biomass storage is $11.50 ($12) per ton, while corn stover, switchgrass, *Miscanthus*, wheat straw, and alfalfa storage costs are assumed to have mean (likeliest) values of $10.50 ($11) per ton.

Establishment and seeding costs (C_{ES})

Corn stover, wheat straw, and forest residue suppliers are assumed to not incur establishment and seeding costs (C_{ES}), while all other feedstock suppliers must be compensated for their establishment

[127] Sohngen et al. (2010); Spelter & Toth, (2009); USDA Forest Service (2003; 2005)
[128] Atchison & Hettenhaus (2003); BRDI (2008); Brechbill & Tyner (2008a); English et al. (2006); Khanna, Dhungana, & Clifton-Brown (2008); Mapemba et al. (2007); Perlack & Turhollow (2002; 2003); Taheripour and Tyner (2008); Tiffany et al. (2006); Vadas et al. (2008)
[129] Although the biomass density for a corn-soybean rotation is assumed to be 0.20, the value used to calculate the average hauling distance for stover from a CS rotation is 0.10 since only half of the acreage is in corn at any given point in time.
[130] Brechbill & Tyner (2008b; 2008a); Huang et al. (2009); McCarl, Adams, Alig, & Chmelik (2000); Perlack & Turhollow (2002); Petrolia (2008); Popp & Hogan (2007)
[131] Storage costs were updated using USDA NASS Agricultural building material prices from 1999-2007 (NASS, 2007a; 2007b).
[132] Duffy (2007); Hess, Wright, & Kenney (2007); Huang et al. (2009); Khanna (2008); Khanna, Dhungana, & Clifton-Brown (2008); Mapemba et al. (2007); Petrolia (2008)

and seeding costs. Costs vary by initial cost, stand length, years to maturity, and interest rate. Stand length for switchgrass ranges between 10 and 20 years[133] with full yield maturity by the third year.[134] *Miscanthus* stand length ranges from 10 to 25 years[135] with full maturity between the second and fifth year.[136] Interest rates used for amortization of establishment costs within the literature range between 4 and 8%.[137] Amortized cost estimates for switchgrass establishment and seeding, adjusted to 2007 costs,[138] are between $30 and $200 per acre.[139] *Miscanthus* establishment and seeding cost estimates vary widely, based on the assumed level of technology and input costs. James, Swinton, & Thelen (2010) report a total rhizome cost (not including equipment and labor) of $8,194 per acre as representative of current costs and $227.61 per acre for a projected cost estimate after technological advancement (2008$). Lewandowski, Scurlock, Lindvall, & Christou (2003) provide a cost range of $1206-2413 per acre (not updated). Jain, Khanna, Erickson, & Huang (2010) estimate the cost of *Miscanthus* establishment in Illinois to be around $1200 per acre for rhizomes and $1215-1650 per acre for plugs. Establishment costs for wood also vary by species and location. Cubbage et al. (2010) report establishment costs of $386-$430 for yellow pine and $520 per acre for Douglas Fir (2008$).

Given the research estimates, switchgrass establishment and seeding costs in this analysis are based on a $250 per acre cost, amortized over 10 years at 10% to yield a mean value of $40 per acre per year in all regions. *Miscanthus* establishment and seeding cost is assumed to have a mean value of $150 per acre per year based on an initial cost of $1250 per acre amortized over 20 years at 10%. Establishment of alfalfa is assumed fixed at $165 per acre, including fertilizer application. Finally, farmed trees are assumed to cost $400 per acre to establish and amortized over 15 years at 10% to yield a mean value of $52 per acre per year.

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[133] Brechbill & Tyner (2008a); de la Torre Ugarte et al. (2009); Duffy & Nanhou (2002); Fike et al., (2006a); Jain, Khanna, Erickson, & Huang (2010); James, Swinton, & Thelen (2010); Khanna (2008); Khanna & Dhungana (2007); Khanna, Dhungana, & Clifton-Brown (2008); Lewandowski, Scurlock, Lindvall, & Christou (2003); Miller & Bender (2008); Mooney, Roberts, English, Tyler, & Larson (2009); Popp & Hogan, 2007; Tiffany et al., 2006

[134]Jain et al. (2010); Kszos et al., 2002; McLaughlin & Kszos, 2005; Popp & Hogan (2007); Walsh (2008)

[135] Atkinson, 2009; Jain et al., 2010; James et al., 2010; Khanna, 2008; Khanna, Dhungana, & Clifton-Brown (2008); Khanna and Dhungana, 2007; Lewandowski et al., 2003

[136] Atkinson, (2009); Clifton-Brown, Long, & Jorgensen (2001); Heaton et al. (2004a); Jain et al. (2010); James, Swinton, & Thelen (2010)

[137] Brechbill & Tyner (2008b; 2008a); Brechbill, Tyner, & Ileleji (2008); Duffy & Nanhou (2002); Jain et al. (2010); Quick (2003); Sokhansanj & Turhollow (2002)

[138] Establishment and Seeding costs were updated using USDA NASS Agricultural fuel and seed prices from 1999-2007 (NASS, 2007a; 2007b).

[139] Duffy (2007); Huang et al. (2009); Khanna, Dhungana, & Clifton-Brown (2008); Perrin et al. (2008); Vadas et al. (2008)

Opportunity costs **(C_{Opp})**

To provide a complete economic model, BioBreak includes opportunity costs of utilizing biomass for ethanol production. Research estimates for corn stover opportunity cost range between $22 and $143 per acre,[140] while the opportunity cost of switchgrass and *Miscanthus* are significantly higher with estimates ranging between $70 and $318 per acre.[141] Estimates for non-specific biomass opportunity cost range between $10 and $76 per acre,[142] depending on the harvest restrictions under CRP contracts. Opportunity costs of woody biomass are estimated to range between $0 and $30 per ton.[143]

Corn stover from a corn-soybean rotation is assumed to have no opportunity cost beyond nutrient replacement cost but corn stover from continuous corn production incurs the forgone profits from switching to continuous corn production from a corn-soybean rotation. Using the rotation calculator provided by the Iowa State University Extension services and assuming a corn price of $4 per bushel, soybean price of $10 per bushel, and a yield penalty of 7 bushels per acre when switching from a corn-soybean rotation to continuous corn production, the lost net returns to switching equate to around $62 per acre.[144] Therefore, a mean value of $62 per acre is used for the opportunity cost of stover from continuous corn production. Given the research estimates for perennial grass opportunity cost, switchgrass and *Miscanthus* grown on Midwest land are assumed to have mean opportunity costs of $150 per acre on high quality and $100 per acre on low quality land. Perennial grasses grown in the Appalachian and South-Central regions are assumed to have lower mean opportunity costs of $75 and $50 per acre, respectively. Wheat straw opportunity cost is assumed to follow a distribution with likeliest value of $2.8 per acre with a range of -$10 to $30 per acre. Negative values for the opportunity costs of wheat straw are based on the potential nuisance cost of wheat straw. Occasionally, straw is burned at harvest to avoid grain planting problems during the following crop season. Forest residue is assumed to have no value in an alternative use or no opportunity cost. While farmed trees have alternative use value, the stumpage fee is assumed to capture the opportunity cost. Finally, alfalfa is assumed to have a two year stand with first year harvest sold for hay at a value of $140 per ton. Second year alfalfa is assumed to have 50% leaf mass sold for protein value at $160 per ton while the remaining 50% is used as a biofuel feedstock. For both years, alfalfa opportunity cost (i.e. land cost) is assumed to be fixed at $175 per acre.

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[140] Khanna & Dhungana (2007); Edwards (2007)
[141] Brechbill & Tyner (2008a); Jain et al. (2010); Khanna & Dhungana (2007); Khanna, Dhungana, & Clifton-Brown (2008)
[142] Khanna, Dhungana, & Clifton-Brown (2008); Mapemba et al. (2008)
[143] Summit Ridge Investments (2007); USDA Forest Service (2003; 2005)
[144] http://www.extension.iastate.edu/agdm/crops/html/a1-20.html

***Biomass yield* (** Y_B **)**

The final parameter in the model is biomass yield per acre of land. Biomass yield is variable in the near and distant future due to technological advancements and environmental uncertainties. Corn stover yield per acre will vary based on the amount of removable corn stover, which depends on soil quality and other topographical characteristics. Harvested corn stover yield has been estimated between 0.7 to 3.8 tons per acre.[145] Potential switchgrass yields range between 0.89 and 17.8 tons per acre,[146] depending on region, land quality, switchgrass variety, field versus plot trial studies, and harvest technique. On average, *Miscanthus* has significantly higher yield projections than switchgrass with estimates ranging between 3.4 and 28 tons per acre when both US and EU yield estimates are considered.[147] U.S. *Miscanthus* yield estimates range between 9 and 28 tons per acre.[148] For woody biomass, Huang et al. (2009) estimated Aspen wood yield of 0.446 dry tons per acre from a densely forested area in Minnesota, while the BRDI (2008) study assumed short-run woody crops yield 5 to 12 tons per acre. Using USDA Forest Service Data for Mississippi, the average removal rate of wood residue in 2006 was around 1.1 tons per acres.[149] In a recent study on 2008 wood production costs, Cubbage et al. (2010) estimate an annual yield of 3.6 and 4.3 tons per acre in North Carolina and the Southern United States, respectively. In the same analysis, Douglas Fir was estimated to provide 4

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[145] Atchison & Hettenhaus (2003); BRDI (2008); Brechbill & Tyner (2008a); Chen et al. (2010); Duffy & Nanhou (2002); Edwards (2007); Huang et al. (2009); Khanna (2008); Khanna & Dhungana (2007); Lang (2002); Perlack & Turhollow (2002); Prewitt et al. (2007); Quick (2003); Sokhansanj & Turhollow (2002); Schechinger & Hettenhaus, (2004); Vadas et al. (2008)

[146] Berdahl, Frank, Krupinsky, Carr, Hanson, & Johnson (2005); Bouton (2002); Brechbill & Tyner (2008a) ; BRDI (2008); Cassida et al. (2005); Chen et al. (2010); Comis (2006); Duffy (2007); Fike et al., (2006a); Fike et al., (2006b); Gibson & Barnhart, (2007); Heaton, Voight, & Long (2004b); Huang et al. (2009); Jain et al. (2010); Khanna & Dhungana (2007); Khanna (2008); Khanna, Dhungana, & Clifton-Brown (2008); Kiniry et al. (2005); Kszos, McLaughlin, & Walsh (2002); Lewandowski et al. (2003); McLaughlin et al. (2002); McLaughlin & Kszos (2005); Muir, Sanderson, Ocumpaugh, Jones, & Reed (2001); Nelson, Ascough, & Langemeie (2006); Ocumpaugh et al. (2003); Parrish, Wolf, Fike, & Daniels (2003); Perrin et al. (2008); Popp & Hogan (2007); Reynolds, Walker, & Kirchner (2000); Sanderson (2008); Schmer, Vogel, Mitchell, Moser, Eskridge, & Perrin (2006); Shinners, Boettcher, Muck, Wimer, & Caser (2006); Taliaferro (2002); Thomason et al. (2005); Tiffany et al. (2006); Vadas et al. (2008); Vogel, Brejda, Walters, & Buxton (2002); Walsh (2008)

[147] Christian, Riche, & Yates (2008); Clifton-Brown & Lewandowski (2002); Clifton-Brown, Long, & Jorgensen (2001);
Clifton-Brown, Stampfl, & Jones (2004); Heaton et al. (2004b; 2004a); Kahle, Beuch, Boelcke, Leinweber, & Schulten (2001); Khanna (2008); Khanna & Dhungana (2007); Khanna, Dhungana, & Clifton-Brown (2008); Lewandowski, Clifton-Brown, Scurlock, & Huisman (2000); Lewandowski et al. (2003); Smeets, Lewandowski, & Faaij (2009); Stampfl, Clifton-Brown, & Jones (2007); Vargas, Andersen, Jensen, & Jorgensen (2002)

[148] Chen et al. (2010); Heaton et al. (2004b; 2004a); Jain et al. (2010); Khanna (2008); Khanna & Dhungana (2007); Khanna, Dhungana, & Clifton-Brown (2008)

[149] 1.1 tons per acre is a lower bound since forestry still had positive net growth over the data period.

and 5.1 tons per acre annually in Oregon and North Carolina, respectively. For wheat straw, the BRDI (2008) study assumed a yield of 1 ton per acre.

For simulation, the mean yield of corn stover is approximately 2 tons per acre. Switchgrass grown in the Midwest has a distribution with a mean (likeliest) value around 4 (3.4) tons per acre on high quality land and 3.1 tons per acre on low quality land.[150] *Miscanthus* grown in the Midwest is assumed to have a mean (likeliest) value of 8.6 (8) tons per acre on high quality land and 7.1 (6) tons per acre on low quality land.[151] Switchgrass grown in the South-Central region has a higher mean yield of around 5.7 tons per acre. For the regions analyzed, the Appalachian region provides the best climatic conditions for switchgrass and *Miscanthus* with assumed mean (likeliest) yields of 6 (5) and 8.8 (8) tons per acre, respectively. Wheat straw, forest residues, and farmed trees are assumed to have mean yields of 1, 0.5, and 5 tons per acre, respectively. First year alfalfa yield is fixed at 1.25 tons per acre (sold for hay value), while second year yield is fixed at 4 tons per acre (50% sold for protein value) resulting in 2 tons per acre of alfalfa for biomass feedstock during the second year.

***Government incentives* (G_S)**

For biomass supply government incentives (G_S), we account for the dollar for dollar matching payments provided in the Food, Conservation, and Energy Act of 2008 (i.e. 2008 Farm Bill) up to $45 per ton of feedstock for collection, harvest, storage and transportation and denote this as "CHST." The CHST payment is considered within the sensitivity analysis rather than the baseline scenario since the program is temporary (two-year) and might not be considered in the supplier's long-run analysis. Although the model is flexible enough to account for any additional policy incentives, the establishment assistance program outlined in the 2008 Farm Bill is not considered since implementation details are not finalized.

[150] Plot trials were evaluated at 80% of their estimated yield.
[151] The *Miscanthus* yield assumptions used in this analysis are lower than previous research has assumed or simulated (Khanna & Dhungana, 2007; Khanna, Dhungana, & Clifton-Brown, 2008; Heaton, Clifton-Brown, Voight, Jones, & Long, 2004a).

Complete Parameter Distribution Assumptions

Table B.1.1 – Processor *DD* parameter distribution assumptions

Parameter	**Feedstock**	**Mean Value in Baseline (Likeliest if Skewed)**	**Distribution**
Oil price (P_{Oil})	All	\$50/barrel \$100/barrel \$150/barrel	Fixed (3 scenarios)
EV	All	0.667	Fixed
Tax (T)	All	\$1.01/gal	Fixed
Coproduct value (V_C)	Stover Switchgrass (All) *Miscanthus* (All) Wheat Straw Farmed Trees Forest Residue Alfalfa	\$0.22/gal \$0.24/gal \$0.24/gal \$0.24/gal \$0.20/gal \$0.20/gal \$0.24/gal	Fixed Fixed Fixed Fixed Fixed Fixed Fixed
Octane (V_O)	All	\$0.10/gal	Fixed
Capital cost (C_I)	All	\$0.82/gal	Normal
Operating costs (C_O)			
Non-enzyme operating cost	All	\$0.92/gal	Fixed
Enzyme cost	All	\$0.70/gal	Normal
Yield (Y_O)	All	70 gal/ton	Normal

Table B.1.2 – Supplier *SC* parameter distribution assumptions

Parameter	Feedstock	Mean Value (Likeliest if Skewed)	Distribution
Nutrient replacement (C_{NR})	Stover	\$13.6/ton (\$14.6)	Min. Extreme
	Switchgrass (All)	\$15.6/ton (\$16.6)	Min. Extreme
	Miscanthus (All)	\$8.35/ton	Normal
	Wheat Straw	\$5.6/ton	Normal
	Farmed Trees	-	-
	Forest Residue	-	-
	Alfalfa (2nd year)	\$62.5/acre (\$15.6/ton)	Fixed
Harvest and maintenance (C_{HM})	Stover	\$43/ton (\$46)	Min. Extreme
	Switchgrass (all)	\$36/ton (\$38)	Min. Extreme
	Miscanthus (all)	\$45/ton (\$48)	Min. Extreme
	Wheat Straw	\$31.5/ton (\$33)	Min. Extreme
	Farmed Trees	\$26/ton	Normal
	Forest Residue	\$26/ton	Normal
	Alfalfa	\$55/acre/harvest	Fixed
Stumpage fee (*SF*)	Farmed Trees	\$20/ton	Normal
Distance fixed cost (*DFC*)	Stover	\$8.50/ton	Normal
	Switchgrass (all)	\$8.50/ton	Normal
	Miscanthus (all)	\$8.50/ton	Normal
	Wheat Straw	\$8.50/ton	Normal
	Farmed Trees	\$10/ton	Normal
	Forest Residue	\$10/ton	Normal
	Alfalfa	\$8.50/ton	Normal
Distance variable cost (*t*)	Stover	\$0.35/ton/mile (\$0.38)	Min. Extreme
	Switchgrass (all)	\$0.35/ton/mile (\$0.38)	Min. Extreme
	Miscanthus (all)	\$0.35/ton/mile (\$0.38)	Min. Extreme
	Wheat Straw	\$0.35/ton/mile (\$0.38)	Min. Extreme
	Farmed Trees	\$0.50/ton/mile (\$0.53)	Min. Extreme
	Forest Residue	\$0.50/ton/mile (\$0.53)	Min. Extreme
	Alfalfa	\$0.35/ton/mile (\$0.38)	Min. Extreme

[a] Average hauling distance is calculated using the formulation by French (1960) for a circular supply area with a square road grid.
[b] Equivalent to 2,205 tons per day delivered to a plant operating 350 days per year.
[c] Switchgrass establishment seeding costs are amortized over 10 years at 10%, *Miscanthus* establishment and seeding costs are amortized over 20 years at 10%, and woody biomass costs are amortized over 15 years at 10%. The values presented in the table are annual payments per acre.
[d] All per acre costs are converted to per ton costs using the yield assumptions provided in the table.
[e] First year with fertilization.
[f] Midwest opportunity cost is assumed to be positively correlated with corn yield through stover yield with a correlation of 0.75.

Table B.1.2 – Continued

Distance[a]	Stover (CC)	26	Fixed
	Stover (CS)	36	Fixed
	Stover/Alfalfa	26	Fixed
	Alfalfa	43	Fixed
	Switchgrass (MW)	19	Fixed
	Switchgrass (MW_{low})	21	Fixed
	Switchgrass (App)	15	Fixed
	Switchgrass (SC)	16	Fixed
	Miscanthus (MW)	13	Fixed
	Miscanthus (MW_{low})	14	Fixed
	Miscanthus (App)	13	Fixed
	Wheat Straw	37	Fixed
	Farmed Trees	17	Fixed
	Forest Residue	53	Fixed
Annual biomass demand (*BD*)	All	77,1750 tons[b]	Fixed
Yield (Y_B)	Stover	2.1 tons	Gamma
	Alfalfa (1st year)	1.25 tons	Fixed
	Alfalfa (2nd year)	4 tons	Fixed
	Switchgrass (MW)	4 tons (3.4)	Max. Extreme
	Switchgrass (MW_{low})	3.1 tons	Log Normal
	Switchgrass (App)	6 tons (5)	Max. Extreme
	Switchgrass (SC)	5.7 tons	Beta
	Miscanthus (MW)	8.6 tons (8)	Max. Extreme
	Miscanthus (MW_{low})	7.1 tons (6)	Max. Extreme
	Miscanthus (App)	8.8 tons (8)	Max. Extreme
	Wheat Straw	1 ton	Normal
	Farmed Trees	5 tons	Normal
	Forest Residue	0.5 tons	Normal
Biomass density (*B*)	Stover (CC)	0.20	Normal
	Stover (CS)	0.10	Normal
	Switchgrass (all)	0.20	Normal
	Miscanthus (all)	0.20	Normal
	Wheat Straw	0.20	Normal
	Farmed Trees	0.20	Normal
	Forest Residue	0.20	Normal
	Alfalfa	0.15	Normal
Storage (C_S)	Stover (CC)	$10.50/ton ($11)	Min. Extreme
	Stover (CS)	$10.50/ton ($11)	Min. Extreme
	Switchgrass (all)	$10.50/ton ($11)	Min. Extreme
	Miscanthus (all)	$10.50/ton ($11)	Min. Extreme
	Wheat Straw	$10.50/ton ($11)	Min. Extreme
	Farmed Trees	$11.50/ton ($12)	Min. Extreme
	Forest Residue	$11.50/ton ($12)	Min. Extreme
	Alfalfa	$10.50/ton ($11)	Min. Extreme

Table B.1.2 – Continued

Establishment and seeding (C_{ES})[c,d]	Stover	-	-
	Switchgrass (all)	$40/acre	Log Normal
	Miscanthus (all)	$150/acre	Log Normal
	Wheat Straw	-	-
	Farmed Trees	$52/acre	Normal
	Forest Residue	-	-
	Alfalfa[e]	$165/acre	Fixed
Opportunity cost (C_{Opp})	Stover (CC)	$62/acre	Beta
	Stover (CS)	-	-
	Switchgrass (MW)	$150/acre[f]	Log Normal
	Switchgrass (MW_{low})	$100/acre	Log Normal
	Switchgrass (App)	$75/acre	Normal
	Switchgrass (SC)	$50/acre	Normal
	Miscanthus (MW)	$150/acre	Log Normal
	Miscanthus (MW_{low})	$100/acre	Log Normal
	Miscanthus (App)	$75/acre	Normal
	Wheat Straw	$2.80/acre ($0)	Max. Extreme
	Farmed Trees	-	-
	Forest Residue	-	-
	Alfalfa (1st year w/ fert)	$175/acre	Fixed

Appendix B.2 – Literature summary

Table B.2.1 – Ethanol production research estimates

Type of Cost	Assumption	Value cited	Value in 2007	Reference
Oil price		$60/barrel		Elobeid et al. (2006)
Ethanol price	Analysis range	$1.50-$3.50/gal		Lambert & Middleton (2010)
	Minimum for industry development	$1.70/gal		Lambert & Middleton (2010)
	Historical trend	$P_{oil}/29$		Elobeid et al. (2006)
EV		0.667		Elobeid et al. (2006)
		0.667		Tokgoz et al. (2007)
Tax credit	Corn	$0.45/gal	$0.45/gal	2008 Farm Bill
	Cellulosic	$1.01/gal	$1.01/gal	2008 Farm Bill
Coproduct credit	Cellulosic		$0.14-.21/gal[a]	Aden et al. (2002)
			$0.16/gal[a]	Khanna & Dhungana (2007)
		2.61 KWH/gal		Aden et al. (2002)
		$0.12/gal[b]		Khanna (2008)
	Rank from low to high excess electricity	Aspen wood Corn stover Poplar Switchgrass		Huang et al. (2009)
	Stover	$0.22/gal	$0.22/gal	Kazi et al. (2010b)
		4.06 kWh/gal	4.06 kWh/gal	Kazi et al. (2010b)
		$0.054/kWh ($0.03-0.06)	$0.054/kWh ($0.03-0.06)	Kazi et al. (2010b)
	Corn	$0.48/gal		Khanna (2008)
Investment cost	69.3 mgy	$197.4 million		Aden et al. (2002)
	55.5 mgy	$231.7 million	$231.7 million	Aden (2008)
	53.4 mgy	$375.9 million	$375.9 million	Kazi et al. (2010b)
	50 mgy	$294 million		Wright & Brown (2007)
	100 mgy	$400 million		Taheripour & Tyner (2008)
	Stover (70 mgy)	$202.2 million (0.46/gal if 10-10)[c]	$0.50[d]	Huang et al. (2009)
	SG (64 mgy)	$212.1 million (0.53/gal if 10-10)	$0.58	
	Hybrid Poplar (68 mgy)	$203.3 million (0.50/gal if 10-10)	$0.545	
	Aspen Wood (86 mgy)	$187 million (0.34/gal if 10-10)	$0.37	
		$0.55/gallon	$0.55/gal	Jiang & Swinton (2008)

[a] Updated using EIA (2008).
[b] Not updated since author did not provide year of estimate.
[c] 10-10 denotes cost is amortized over 10 years at 10%.
[d] Updated using building materials price index.
[e] Operating costs excluding feedstock cost, enzyme cost, and co-product credit.
[f] Operating costs excluding feedstock cost, enzyme cost, co-product credit, depreciation, and minimum investment return.
[g] Updated using machinery price index (NASS, 2007a; 2007b).
[h] Consistent with a 65% efficiency of theoretical yield.

Table B.2.1 – Continued

Plant life	Biochemical	20 years		Kazi et al. (2010b)
Other costs	Partial variable costs	$0.11/gal		Aden et al. (2002)
	"Other" costs	$0.11/gal		Aden et al. (2002)
	Total non-feedstock costs	$1.48/gal		Chen et al. (2010)
	Operating costs[e]	$1.84/gal	$1.84	Kazi et al. (2010b)
	Adjusted operating cost[f]	$0.92	$0.92	Kazi et al. (2010b)
Enzyme cost		$0.07-0.20/gal		Aden et al. (2002)
		$0.32/gal	$0.32/gal	Aden (2008)
	2012 target	$0.10/gal		Aden (2008)
		$0.14-0.18/gal		Bothast (2005)
		$0.40-$1.00/gal	$0.40-1.00/gal	Industry Source
		$0.69/gal	$0.69/gal	Kazi et al. (2010b)
		$0.10-0.25/gal		Tiffany et al. (2006)
Operating costs	Stover	$1.42/gal[g]	$1.58/gal	Huang et al. (2009)
	SG (crop)	$1.73/gal	$1.92/gal	
	SG (grass)	$1.86/gal	$2.06/gal	
	Hybrid Poplar	$1.83/gal	$2.03/gal	
	Aspen Wood	$1.56/gal	$1.73/gal	
		$1.10/gal	$1.10/gal	Jiang & Swinton (2008)
Ethanol yield (Cellulosic)		87.9		Aden et al. (2002)
	Stover			Aden (2008)
	Current	71.9		
	Theoretical	112.7		
	2012 target	90		
		80-120		Atchison & Hettenhaus (2003)
		80-90		BRDI (2008)
	Woody	89.5		
		79		Chen et al. (2010)
		96		Comis (2006)
		60-140		Crooks (2006)
	Stover	89.8		Huang et al. (2009)
	Switchgrass	82.7		
	Hybrid Poplar	88.2		
	Aspen Wood	111.4		
		54.4		Jiang & Swinton (2008)
	Stover			Kazi et al. (2010b)
	Current[h]	69.5		
	Theoretical	106.9		
		87.3		Khanna (2008)
		79.2		Khanna & Dhungana (2007)
		60-140		Krissek (2008)
		72		McAloon et al. (2000)
		80		Perlack & Turhollow (2002)
		70		Petrolia (2008)
		67.8-89.7		Tiffany et al. (2006)
		70		Tokgoz et al. (2007)

Table B.2.1 – Continued

Plant size	Cellulosic Stover	2294-4408 tons/day 2206 tons/day		Huang et al. (2009) Kazi et al. (2010b)
Online Days		350 350 350		Aden et al. (2002) Huang et al. (2009) Kazi et al. (2010b)

Table B.2.2 – Harvest and maintenance[a]

Type of Feedstock	Type of Cost	Cost per ton (cited)	Cost per ton (2007$)	Reference
Corn stover	Baling and staging	26	47	Aden (2008)
	Custom Harvest			Brechbill & Tyner (2008a)
	Bale	7.5	7.5	
	Rake and Bale	8.8	8.8	
	Shred, Rake, and Bale	10.7	10.7	
	Harvest	14	14	Edwards (2007)
	Baling, stacking and grinding	26	45	Hess et al. (2007)
	Combine, Shred, Bale and Stack	19.2	24.3	Huang et al. (2009)
	Harvest cost	19.6	36	Jiang & Swinton (2008)
	Harvest	35.4-36.6	35.4-36.6	Khanna (2008)
	Harvest and Bale	7.3	7.3	Lambert & Middleton (2010)
	Collection	31-36	66-77	McAloon et al. (2000)
	Collection	35-46	64-84	McAloon et al. (2000)
	Collection	17.7	17.7	Perlack (2007, Presentation)
	Up to Storage	20-21	36-39	Sokhansanj & Turhollow (2002)
		28	36	Suzuki (2006)
Corn stover or Switchgrass	Move to fieldside	2	2	Brechbill & Tyner (2008a)
Switchgrass	Custom Harvest			Brechbill & Tyner (2008a)
	Bale	2.01	2.01	
	Rake and Bale	3.09	3.09	
	Shred, Rake and Bale	4.79	4.79	
	Harvest	32	32	Duffy (2007)
	Harvest (square bales)	21.9	27.8	Huang et al. (2009)
	Total production cost	54.4	54.4	Jiang & Swinton (2008)
	Harvest	27.8-34.7	27.8-34.7	Khanna (2008)
	Harvest, maintenance and establishment	123.5/acre	210/acre	Khanna & Dhungana (2007)
	Harvest	35	58	Khanna, Dhungana, & Clifton-Brown (2008)
	Collection	12-22	16-28	Kumar & Sokhansanj (2007)

[a] Harvest and maintenance costs were updated using USDA NASS Agricultural fuel, machinery and labor prices from 1999-2007 (NASS, 2007a; 2007b).
[b] The Jenkins et al. (2009) value was based on a summary of the literature and does not have a relevant year for cost.
[c] Assume a conversion of 0.59 for green tons to dry tons.
[d] Price not updated.

Table B.2.2 – Continued

Switchgrass (cont.)	Maintenance and Fertilization 0 lb N/ac 60 lb N/ac 120 lb N/ac 180 lb N/ac Harvest cost (function of yield) 7.7 tons/acre 12.5 tons/acre 2.4 tons/acre 7.2 tons/acre Harvest Weed Control Mow, Rake, Bale, Equip, Repair, Interest, Operating Capital	 17.23/acre 46.5/acre 72.7/acre 99/acre 200/acre 312/acre 79/acre 190/acre 15 9.4/acre 243/acre	 17.23/acre 46.5/acre 72.7/acre 99/acre 200/acre 312/acre 79/acre 190/acre 26 9.4/acre (08$) 243/acre	Mooney et al. (2009) Mooney et al. (2009) Perrin et al. (2008) University of Tennessee (2009)
Prairie grasses (include SG)	Harvest	17.7-19.3		Tiffany et al. (2006)
Miscanthus	Harvest Harvest, maintenance, and establishment Harvest	18.7-32.7 301/acre 33	18.7-32.7 512/acre 54	Khanna (2008) Khanna & Dhungana (2007) Khanna, Dhungana, & Clifton-Brown (2008)
Straw	Harvest and Bale	7.3	7.3	Lambert & Middleton (2010)
Non-specific		10-30 23	15-45 38	Mapemba et al. (2007) Mapemba et al. (2008)
Hybrid Poplar and Aspen Wood	Logging Cost Range Assumed Chipping Cost Range Assumed (Minnesota)	 14-28 14.5 12-27 12.7	 17.8-34.6 18.4 15.2-34.3 16.1	Huang et al. (2009)
Woody Biomass	Roadside Stumpage Harvest/Collection Collect and transport woody slash 2.8 m Aspen wood stumpage Up to roadside	40-46 4 17-29/acre 24.3/Gt 31.2/dt 51.9 30-50	40-46 4 17-29/acre 24.3/Gt 31.2/dt 66 30-50[b]	BRDI (2008) BRDI (2008) BRDI (2008) Han et al. (2010) Huang et al. (2009) Jenkins et al. (2009)

Table B.2.2 – Continued

Woody Biomass (continued)	Up to roadside and on truck	25/dt	25/dt[d]	Sohngen et al. (2010)
	Up to roadside and on truck (high)	34/dt	34/dt (09$)	Sohngen et al. (2010)
	Delivered cost range	34-65	34-65 (09$)	Sohngen et al. (2010)
	Residue delivered			
	West	56/GMT	86/dt[c] (08$)	Spelter & Toth, (2009)
	North	49/GMT	75/dt[c] (08$)	Spelter & Toth, (2009)
	South	42/GMT	66/dt[c] (08$)	Spelter & Toth, (2009)
	Northeast	38/GMT	58/dt[c] (08$)	Spelter & Toth, (2009)
	Cut and extract to roadside	35-87[d]		USDA Forest Service (2003; 2005)

Table B.2.3 – Nutrient and replacement[a]

Type of Feedstock	Type of Cost	Cost per ton (cited)	Cost per ton (2007$)	Reference
Corn stover		7	14.4	Aden et al. (2002)
		6.4-12.2[b]		Atchison & Hettenhaus (2003)
		15.6	15.6	Brechbill & Tyner (2008a)
		10.2	14.1	Hoskinson et al. (2007)
		7.3	10	Huang et al. (2009)
		6.5	13.7	Jiang & Swinton (2008)
	Replace N, P, K	21.7	21.7 (09$)	Karlen (2010)
	Whole plant harvest	9.7	13.3	Karlen & Birrell (Presentation)
	Cob & top 50% harvest	9.5	13.1	Karlen & Birrell (Presentation)
	Bottom 50% harvest	10.1	13.9	Karlen & Birrell (Presentation)
		4.6	8.4	Khanna & Dhungana (2007)
		10	21	Perlack & Turhollow (2003)
		4.2	4.2	Petrolia (2008)
Corn stover or Straw		11.1	15.4	Lambert & Middleton (2010)
Switchgrass		10.8	19.8	Khanna, Dhungana, & Clifton-Brown (2008)
		6.7	12.1	Perrin et al. (2008)
	Fertilizer, Equipment, Labor	84/acre	84/acre (08$)	UT (2008)
Miscanthus		2.5	4.6	Khanna, Dhungana, & Clifton-Brown (2008)
		4.2	7.7	Cost using average fertilizer rates from literature summarized in Khanna, Dhungana, & Clifton-Brown (2008) and updated Khanna, Dhungana, & Clifton-Brown (2008) costs

[a] Nutrient and Replacement costs were updated using USDA NASS Agricultural Fertilizer Prices from 1999-2007 (NASS, 2007a,b).
[b] Price not updated.

Table B.2.4 – Distance

Distance (miles)	Type	Reference
10-50	One-way	Atchison & Hettenhaus (2003)
5-50	One-way	Brechbill & Tyner (2008b; 2008a)
75	One-way max	BRDI (2008)
50	One-way max	English et al. (2006)
50	Round-trip	Khanna, Dhungana, & Clifton-Brown (2008)
46-134	Round-trip	Mapemba et al. (2007)
22-61	One-way	Perlack & Turhollow (2002)
16.6-47	One-way average	Perlack & Turhollow (2002)
22-62	One-way	Perlack & Turhollow (2003)
83	One-way (wood)	Sohngen et al. (2010)
46-138	One-way range (wood)	Sohngen et al. (2010)
50	One-way (wood)	Spelter & Toth, (2009)
50	One-way max	Taheripour & Tyner (2008)
50	One-way	Tiffany et al. (2006)
100	One-way (wood)	USDA Forest Service (2003; 2005)
50	One-way	Vadas et al. (2008)

Table B.2.5 – Transportation cost[a]

Type of Feedstock	Type of Cost	Cost cited	Cost (2007$)	Reference
Corn stover	Per ton	13	31	Aden et al. (2002)
	10 miles	3.4		Atchison & Hettenhaus (2003)
	15 miles	5.1		
	30 miles	10.2		
	40 miles	13.5		
	50 miles	17[b]		
	Own equipment (per ton)			Brechbill & Tyner (2008a)
	10 miles	3.3-6.2	3.3-6.2[e]	
	20 miles	4.7-7.5	4.7-7.5	
	30 miles	6-8.9	6-8.9	
	40 miles	7.3-7.7	7.3-7.7	
	50 miles	8.7-9	8.7-9	
	Per ton	8.9	12.5	English et al. (2006)
	Per ton	10.3	27	Hess et al. (2007)
	DFC	6.9	9.71	Huang et al. (2009)
	t	0.16	0.23	
	t[c]	0.15	0.35	Kaylen et al. (2000)
	Max t for positive NPV	0.28	0.66	Kaylen et al. (2000)
	t	0.16	0.38	Kumar et al. (2003)
	DFC	3.6	8.6	
	t	0.08-0.29	0.17-0.63	Kumar et al. (2005)
	DFC[d]	4.5	9.8	
	DFC range	0-6	0-13.3	
	Per ton	10.8	10.8	Perlack (2007, Presentation)
	Per ton	4.2-10.5	11-27.7	Perlack & Turhollow (2002)
	t			Petrolia (2008)
	0-25 miles	0.13-0.23	0.13-0.23	
	25-100 miles	0.10-0.19	0.10-0.19	
	>100 miles	0.09-0.16	0.09-0.16	
	DFC square bales	1.7	1.7	
	DFC round bales	3.1	3.1	
	t	0.18	0.32	Searcy et al. (2007)
	DFC	4	7.3	
	Per ton	10.9	13.8	Vadas et al. (2008)

[a] Transportation costs were updated using USDA NASS Agricultural fuel prices from 1999-2007 (NASS, 2007a; 2007b).
[b] Prices not updated.
[c] *t* is distance variable cost in per ton per mile.
[d] *DFC* is distance fixed cost per ton.
[e] Authors used 2006 wages and March 2008 fuel costs.

Table B.2.5 – Continued

Corn stover or Switchgrass	Average t	0.20	0.20	Brechbill & Tyner (2008b; 2008a)
	Custom loading	1.15	1.15	Brechbill & Tyner (2008a)
	Custom t	0.28	0.28	
	Owned t	0.12	0.12	
	Custom per ton			
	10 miles	3.9	3.9	
	20 miles	6.7	6.7	
	30 miles	9.5	9.	
	40 miles	12.2	12.2	
	50 miles	15	15	
Switchgrass	Own equipment (per ton)			Brechbill & Tyner (2008a)
	10 miles	3.1-3.9	3.1-3.9[e]	
	20 miles	4.5-5.3	4.5-5.3	
	30 miles	5.8-6.6	5.8-6.6	
	40 miles	7.2-8	7.2-8	
	50 miles	8.5-9.3	8.5-9.3	
	Per ton	14.8	14.8	Duffy (2007)
	DFC	3.4	4.8	Huang et al. (2009)
	t	0.16	0.23	
	Per ton	19.2-23	27-32.4	Kumar & Sokhansanj (2007)
	Per ton	13	28	Perrin et al. (2008)
	Stage and Load	19/acre	19/acre (08$)	UT (2009)
	Per ton	10.9	13.8	Vadas et al. (2008)
Native Prairie (include SG)	Per ton	4[b]		Tiffany et al. (2006)
Switchgrass or *Miscanthus*	Per ton for 50 miles	7.9	17.1	Khanna, Dhungana, & Clifton-Brown (2008)
Non-specific	Per ton	7.4-19.3	13.7-35.6	Mapemba et al. (2007)
	Per ton	14.5	31.5	Mapemba et al. (2008)
Hybrid Poplar and Aspen Wood	*DFC*	4.13	5.8	Huang et al. (2009)
	t	0.16	0.23	
Woody Biomass	t	0.22	0.22	Sohngen et al. (2010)
	Per ton	11-22	11-22	Summit Ridge Investments (2007)
	t	0.2-0.6 Used 0.35[b]		USDA Forest Service (2003; 2005)
Wood	t	0.20-0.60	0.20-0.60	Jenkins et al. (2009)

Table B.2.6 – Storage cost[a]

Type of Feedstock	Type of Cost	Cost per ton (cited)	Cost per ton (2007$)	Reference
Corn stover		4.4	5.6	Hess et al. (2007)
		4.4-22	4.4-22	Khanna (2008)
	Round bales	6.8	6.8	Petrolia (2008)
	Square bales	12.9	12.9	
Stover or Switchgrass	Square bales	7.3	7.9	Huang et al. (2009)
Switchgrass		16.7	16.7	Duffy (2007)
		4.4-21.7	4.4-21.7	Khanna (2008)
		4.1	5.2	Khanna, Dhungana, & Clifton-Brown (2008)
Miscanthus		4.6-23.5	4.6-23.5	Khanna (2008)
		4.4	5.5	Khanna, Dhungana, & Clifton-Brown (2008)
Non-specific		2	2.2	Mapemba et al. (2008)
Hybrid Poplar or Aspen Wood	Keep on stump until needed	0	0	Huang et al. (2009)

[a] Storage costs were updated using USDA NASS Agricultural building material prices from 1999-2007 (NASS, 2007a; 2007b).

Table B.2.7 – Establishment and seeding cost[a]

Type of Feedstock	Type of Cost	Land rent included	Cost per acre (cited)	Cost per acre (2007$)	Reference
Switchgrass		Yes	200	200	Duffy (2007)
	Grassland	No	134	180	Huang et al. (2009)
	Cropland (includes fertilizer)		161	216	
	Seed and fertilizer cost per acre (no equip/machinery)	No	171	171 (08$)	James et al. (2010)
	PV per ton	No	7.2/ton	12.6/ton	Khanna, Dhungana, & Clifton-Brown (2008)
	10 yr PV per acre		142.3	249	
	Amortized				
	4% over 10 years		17.3	30.3	
	8% over 10 years		20.7	36.3	
	Plots with seeding:				
	2.5 lb/acre	No	150	150	Mooney et al. (2009)
	5 lb/acre	No	202.6	202.6	
	7.5 lb/acre	No	255	255	
	10 lb/acre	No	306.6	306.6	
	12.5 lb/acre	No	359	359	
		No	25.8	46	Perrin et al. (2008)
		Yes	85.5	153	
	Prorated Establishment and Reseeding (10 years)		45.7	45.7 (08$)	UT (2009)
		Yes	72.5-110	88.5-134	Vadas et al. (2008)
Miscanthus	Plugs	No	3000-4000/ha	1215-1619/ac	Jain et al. (2010)
	Rhizomes in Illinois	No	2957/ha	1197/ac	
	Total rhizome cost per acre	No	8,194	8,194 (08$)	James et al. (2010)
	Total rhizome cost per acre - projected	No	228	228 (08$)	
	PV per ton	No	2.3/ton	4/ton	Khanna, Dhungana, & Clifton-Brown (2008)
	20 yr PV per acre		261	457	
	Amortized				
	4% over 20 years		19	33.2	
	8% over 20 years		26.2	45.9	
	Total	No	1206-2413		Lewandowski et al. (2003)
	Amortized				
	4% over 20 years		88-175	176-350	
	8% over 20 years		121-242	242-484	

[a] Establishment and seeding costs were updated using USDA NASS Agricultural fuel and seed prices from 1999-2007 (NASS, 2007a; 2007b).

[c] No equipment or labor cost.

Table B.2.7 – Continued

Prairie grass	Total seed cost per acre[c]	No	536	536 (08$)	James et al. (2010)
Mixed Grasses	Total seed cost per acre[c]	No	297	297 (08$)	James et al. (2010)
Hybrid Poplar	Total cutting cost per acre	No	242	242 (08$)	James et al. (2010)
	Includes nutrients (cropland)	No	35	47	Huang et al. (2009)
Timber	Yellow Pine (South average)		386	386 (08$)	Cubbage et al. (2010)
	Yellow Pine (NC)		430	430 (08$)	
	Douglas Fir (NC,OR)		520	520 (08$)	

Table B.2.8 – Opportunity cost[a]

Type of Feedstock	Type of Cost	Cost per acre (cited)	Cost per acre (2007$)	Reference
Corn stover	Lost profits when switch to CC	94-140		Scenarios derived using Duffy (2010)
	Feed value less harvest and nutrient cost	24/ton	245/ton	Edwards (2007)
	@ 2.4 tons/acre	57/acre	57/acre	
	Lost profits	22-58	22-58	Khanna & Dhungana (2007)
Switchgrass	Cash Rents	70 (14/ton)	70 (14/ton)	Brechbill & Tyner (2008a)
	Forgone profits per ton	46-103/mt	42-93/ton	Jain et al. (2010)
	Lost profits	78-231	78-231	Khanna & Dhungana (2007)
	Cash rental rate – alternative land use (TN)	68	68	Mooney et al. (2009)
Switchgrass or *Miscanthus*	Forgone profits – Michigan	366/ha	148/ac	Jain et al. (2010)
	Forgone profits – Illinois	785/ha	318/ac	
	Lost profits	78	76	Khanna, Dhungana, & Clifton-Brown (2008)
Miscanthus	Forgone profits per ton	19-103/mt	17-93/ton	Jain et al. (2010)
	Lost profits	78-231	78-231	Khanna & Dhungana (2007)
Non-specific		78	76	Khanna, Dhungana, & Clifton-Brown (2008)
	Lost CRP payments if harvest every year	35	36	Mapemba et al. (2008)
	Lost CRP if harvest once every 3 years	10.1	10.4	
	Non-CRP land crops	10/ton	10.3/ton	
Woody Biomass	Alternative use	0-25	0-25	Summit Ridge Investments (2007)
	Chip value	30/ton	30/ton[b]	USDA Forest Service (2003; 2005)

[a] Opportunity costs were updated using USDA NASS Agricultural land rent prices from 1999-2007 (NASS, 2007a; 2007b).
[b] Price not updated since no year was provided for initial estimate.

Table B.2.9 – Yield

Biomass Type	Assumptions	Estimated Yield (tons acre^{-1})	Location	Reference
Corn stover		2-3.8		Atchison & Hettenhaus (2003)
	130 bu/acre yield	0-2.6		
	170 bu/acre yield	0-3.6		
	200 bu/acre yield	0-4.3		
		3		BRDI (2008)
	Bale	1.62	IN	Brechbill & Tyner (2008a)
	Rake and Bale	2.23		
	Shred, Rake and Bale	2.98		
	No-till	0.67	Average	Chen et al. (2010)
	Four scenarios	1.5, 3, 4, and 6	IA	Duffy & Nanhou (2002)
		2.4	IA	Edwards (2007)
	Produced	2.54	MN	Huang et al. (2009)
	Previous study	1.6	Michigan	James et al. (2010)
	Produced (150 bu/ac)	2.93	Corn Belt	Jiang & Swinton (2008)
	Harvested (50%)	1.46	Corn Belt	
	Produced	2.4-4	IL	Khanna (2008)
	Delivered	1.8-1.9		
	Soil tolerance	2.02	IL	Khanna & Dhungana (2007)
	Total produced			Lang (2002)
	125 bu/acre	3.5		
	140 bu/acre	3.9		
	>140 bu/acre	4		
		1.1		Perlack & Turhollow (2002)
	Collected	0.8-2.2	KY	Prewitt et al. (2007)
	Total produced	4.2	IA	Quick (2003)
	Removable	2.9		
	Collected (trial)	1.25-1.5	IA, WI	Schechinger & Hettenhaus (2004)
	Produced	3.6	Midwest	Sokhansanj & Turhollow (2002)
	Delivered	1.5		
	2000-2005 mean	2.3-3	WI	Vadas et al. (2008)

[a] The first value is derived using a general conversion factor of 0.64 dry metric tons per cubic meter (DMT/m^3) for softwoods. The yields in parentheses are based on conversion factors provided by engineeringtoolbox.com of 0.35-0.60 DMT/m^3 and 0.53 DMT/m^3 for Yellow Pine and Douglas Fir. (Accessed 9-15-2010) http://www.engineeringtoolbox.com/wood-density-d_40.html

Table B.2.9 – Continued

Switchgrass	Field trials		ND	Berdahl et al. (2005)
	Mean	1.1-4.1		
	Strains:			
	Dacotah	1.1-4.2		
	ND3743	0.9-3.9		
	Summer	1.2-4.4		
	Sunburst	1.4-5.6		
	Trailblazer	1.2-4.9		
	Shawnee	1.1-4.5		
	OK NU-2	0.9-4.2		
	Cave-in-Rock	1-4.3		
	Kanlow (avg)	5.9	AL	Bouton (2002)
	Alamo (avg)	6.0		
		4.2-10.3		BRDI (2008)
		5	IN	Brechbill & Tyner (2008a)
	Alamo (3-4 years)	4.9-8.8	TX	Cassida et al. (2005)
	Caddo (3-4 years)	2.2-2.7		
	Alamo (3 years)	4 .8	LA	
	Caddo (3 years)	0.5		
	Alamo (3 years)	7.5	AR	
	Caddo (3 years)	3.3		
	Simulated (MISCANMOD)	3.8	US Average	Chen et al. (2010)
		7-16	Southeast	Comis (2006)
		5-6	Western Corn Belt	
		1-4	ND	
	POLYSIS assumption	4.9	Northeast	de La Torre Ugarte et al. (2003)
		5.8	Appalachian	
		6	Corn Belt	
		4.8	Lake States	
		5.5	Southeast	
		4.3	Southern Plains	
		3.5	Northern Plains	
		4	IA	Duffy (2007)
	Plot trials	6.3	SE	Fike et al. (2006a)
		4.6-8.5		
	CIR (1 cut)	3.9-7.3	Southeast (6)	Fike et al. (2006b)
	Shelter (1 cut)	3.7-6.8		
	Alamo (1 cut)	4.8-9.8		
	Kanlow (1 cut)	5.4-9.5		
	CIR (2 cut)	5.8-9.5		
	Shelter (2 cut)	4.9-9.1		
	Alamo (2 cut)	6-10		
	Kanlow (2 cut)	6-9.5		
		1-4	IA	Gibson & Barnhart (2007)
		2-6.4		
	Peer-reviewed articles	4.5		Heaton et al. (2004b)
	Cropland and grassland	4.9	MN	Huang et al. (2009)

Table B.2.9 – Continued

Switchgrass (continued)	Average model yield (range)	6.8 (3.6-17.8)	Midwest	Jain et al. (2010)
	Farm-gate yield (annualized yield after losses)	3.8-4.2	Midwest	
	Average observed peak yield	6.6	Midwest	
	Assumption	4	Southern Michigan	James et al. (2010)
	Assumption (previous studies)	3.6	Corn Belt	Jiang & Swinton (2008)
	Delivered	2.3-2.5	IL	Khanna (2008)
	Field Trials	2.6	IA, IL	Khanna & Dhungana (2007)
	Delivered yield (years 3-10)	3.1	IL	Khanna, Dhungana, & Clifton-Brown (2008)
	Peak Yield	4.2	IL	
	10 year PV	19.7	IL	
	3 years of data (avg)	5.5 7.7 8.3-10	LA AR TX	Kiniry et al. (2005)
	7 years of data (avg)	6.6	TX	
	Assumptions			Kszos et al. (2002)
	Lake states	4.8		
	Corn belt	6		
	Southeast	5.5		
	Appalachian	5.8		
	North Plains	3.5		
	South Plains	4.3		
	North East	4.9		
	Plots	4	Iowa	Lemus et al. (2002)
	Research blocks	7.1 (average) 9.8 (best)	Southern and Mid-Atlantic	Lewandowski et al. (2003)
	Alamo (1 cut)	5.4-5.9 11.6	TX, Upper South AL	Lewandowski et al. (2003)
	Alamo (2 cut)	15.4	AL	
	Kanlow (1 cut)	4.5-5.5 8.3	TX, Upper South AL	
	Kanlow (2 cut)	10.3	AL	
	Kanlow (3-4 years)	5	Britain	
	Cave-in-Rock (1 cut)	2.4-4.2 4.2	TX, Upper South AL	
	Cave-in-Rock (2 cut)	4.6	AL	
	Cave-in-Rock (3-6 years)	4.7	Britain	

Table B.2.9 – Continued

Switchgrass (continued)	Calibrated values for 2008 (assumed 2% growth following 2008)	3.5-6.5 5.2-6.4 3.8-6.5 4.5-6.0 3 4.8-6.0 3.2-6.2 3.5-6.3 4.4-6.5	Appalachian Corn Belt Delta States Lake States Mountain States Northern Plains Northeast Southern Plains Southeast	Marshall & Sugg (2010)
	US average	4.2		McLaughlin et al. (2002)
	Farm trials (avg)			McLaughlin & Kszos (2005)
	Alamo (1 cut)	6.2	VA, TN, WV, KY, NC	
	Alamo (1 cut)	6-8.5	TX, AR, LA	
	Alamo (1 cut)	5.4	IA	
	Alamo (1 cut)	5.8-7.2	AL, GA	
	Alamo (2 cut)	7	VA, TN, WV, KY, NC	
	Alamo (2 cut)	7.2-10.3	AL	
	Kanlow (1 cut)	6.2	VA, TN, WV, KY, NC	
	Kanlow (1 cut)	5.8	IA	
	Kanlow (1 cut)	5.2-7	AL, GA	
	Kanlow (1 cut)	9.2	NE	
	Kanlow (2 cut)	6.9-8.1	AL	
	Cave-in-rock (1 cut)	7.3	NE	
	Rockwell (1 cut)	4.2	KS	
	Shelter (1 cut)	4.2	KS	
	Sunburst (1 cut)	4.9	ND	
	Trailblazer (1 cut)	4.4	ND	
	Best	12.2	VA, TN, WV,	
	Alamo (1 cut)		KY, NC	
	Alamo (1 cut)	11	TX, AR, LA	
	Alamo (1 cut)	7.8	IA	
	Alamo (1 cut)	15.4	AL	
	Alamo (2 cut)	11.3	VA, TN, WV, KY, NC	
	Alamo (2 cut)	15.4	AL	
	Kanlow (1 cut)	10.4	VA, TN, WV, KY, NC	
	Kanlow (1 cut)	11	AL, GA	
	Sunburst (1 cut)	6.2	ND	
	Trailblazer (1 cut)	5.4	ND	
	3 experiments on loss	3.8-6.7	Italy	Monti et al. (2009)
	Sustainable yield (124 kg N/acre)	6.7	U.S.	
	Plots – varying seed and nitrogen	3.8-7.9	TN	Mooney et al. (2009)
	One year max – plot	10.2	TN	
	Max (Alamo)	10	TX	Muir et al. (2001)
	Average (2 sites)	4.8-6.5		

Table B.2.9 – Continued

Switchgrass (continued)	Predicted yields		KS	Nelson et al. (2006)
	0-200 lbs/acre N	2.5-5.9		
	100 lbs/acre N	4.6		
	Alamo (1 cut)	1.2-9	Texas	Ocumpaugh et al. (2003)
	Alamo (2 cut)	1.3-8.6		
	Upland (1 cut)	4.8-5.3		Parrish et al. (2003)
	Upland (2 cut)	6.5-6.7		
	Lowland (1 cut)	6.6-7		
	Lowland (2 cut)	6.8-7.3		
	Farm-scale	2.2 (5 year avg) (Range = 1.7-2.7) 3.1 (10 year avg) (Range = 2.6-3.5)	SD, NE	Perrin et al. (2008)
	First	0	AR	Popp & Hogan (2007)
	Second year	3		
	Third+ year	5		
	Cave-in-Rock	2.2	Northern Illinois	Pyter et al. (2007)
	3 year avg	5.2	Central Illinois	
		2.7	Southern Illinois	
	Previous Literature	4.5-6.7		Reijnders (2010)
	One-cut range	5-9	TN	Reynolds et al. (2000)
	Two-cut range	6.8-10.3		
	Cave-in-rock (2 cut)	8.7		
	Alamo (2 cut)	8.9		
	Kanlow (2 cut)	8.2		
	Shelter (2 cut)	8.1		
	Cave-in-Rock (2 cut)	2.8	PA	Sanderson (2008)
	Shawnee (2 cut)	2.7		
	Trailblazer (2 cut)	2.6		
	Mean (2 cut)	2.7		
	Cave-in-Rock (3 cut)	3.2		
	Shawnee (3 cut)	3.2		
	Trailblazer (3 cut)	3.2		
	Mean (3 cut)	3.2		
	Field Trials		Northern Great Plains	Schmer et al. (2006)
	Mean	0.5-3.2		
	Range	0-6.4		
		3.6-8.9 (previous)	US	Shinners et al. (2006)
	Plot trials	2.3-4 (own)	Northern	
	80% of *Miscanthus*	6.7	Poland	Smeets et al. (2009)
	2004	7.1	Hungary	
		5.4	United Kingdom	
		9	Italy	
		5.8	Lithuania	
	2030 (1.5% increase/year)	9.4	Poland	
		9.8	Hungary	
		7.6	United Kingdom	
		12	Italy	
		8	Lithuania	

Table B.2.9 – Continued

Switchgrass (continued)	Alamo	1.6	KS	Taliaferro (2002)
		2.8	AR	
		2.8	VA	
		2.8	OK	
	Kanlow	1.4	KS	
		2.9	AR	
		2.5	VA	
		2.8	OK	
	One cut	5.8	OK	Thomason et al. (2005)
	Two Cut	5.6		
	Three Cut	7.3		
	Max Yield (2 harvest)	16.4		
		4	Northern Plains	Tiffany et al. (2006)
	Nitrogen level	4-5.8	Upper Midwest	Vadas et al. (2008)
	Plot trials	5.2-5.6	IA	Vogel et al. (2002)
		4.7-5	NE	
	Alamo	5.4-6.9	18 sites	Walsh (2008)
	Kanlow	5.2-6.9	18 sites	
	Max one year	15.4	AL	
Grasses	County-scale		Pacific NW	Banowetz et al. (2008)
	Perennial ryegrass	3.4-4.1		
	Tall fescue	4.1-6.2		
	Creeping red fescue	2.2-3.4		
Mixed grasses	Assumption	3.5		James et al. (2010)
Prairie grasses	Assumption	2.14		James et al. (2010)
Wheat straw		1		BRDI (2008)
	Estimated	0.27	Average	Chen et al. (2010)
Miscanthus	Simulated (MISCANMOD)	11.6	U.S. average	Chen et al. (2010)
	Field experiment	5.7 (14 year) 3.4-11.7 (3 year)	EU	Christian et al. (2008)
	First year avg	0.85	Germany	Clifton-Brown & Lewandowski (2002)
	First year max	1.3		
	Second year avg	2.8		
	Second year max	4.3		
	Third year avg	7.3		
	Third year max	11.4		
	First year avg	0.9	EU	Clifton-Brown et al. (2001)
	First year max	2.6		
	First year min	0.2		
	Second year avg	3.8		
	Second year max	12		
	Third year max	18.2		
	Peak	7.5-17.2	EU	Clifton-Brown et al. (2004)
	Delayed	4.3-11.6		
	Projection	13.4 (mean) 10.9-17.8		Heaton et al. (2004a)
	Peer-reviewed articles	10	US/EU	Heaton et al. (2004b)

Table B.2.9 – Continued

Miscanthus (continued)	3 year state avg	13.2	Illinois	Heaton et al. (2008)
	3 year max state avg	17	Illinois	
	Average model yield (range)	19 (0-27.7)	Midwest	Jain et al. (2010)
	Farm-gate yield (annualized yield after losses)	6.3-8.6	Midwest	
	Average observed peak yield	16.6	Midwest	
	Assumption	10	Michigan	James et al. (2010)
	Assumption	9.8	Southern Michigan	James et al. (2010)
	Above ground	6.6-14.9	Germany	Kahle et al. (2001)
	Mean harvested	5.2		
	Potential	12-18	IL	Khanna (2008)
	Delivered	8.1-8.5		
	Simulated	8.9	IL	Khanna & Dhungana (2007)
		14.5 avg 12-17 range 114.6 (20 year PV)	IL	Khanna, Dhungana, & Clifton-Brown (2008)
	Autumn yields w/o irrigation	4.5-11.2	EU	Lewandowski et al. (2000)
	Yield range (high end irrigated)	0.9-19.6	EU	
		1.8-19.6	EU	Lewandowski et al. (2003)
	3 year average	9.8	Northern Illinois	Pyter et al. (2007)
		15.5	Central Illinois	
		15.8	Southern Illinois	
	1 year	14.1	Urbana, Illinois	
	Previous Literature	4.5-5.8		Reijnders (2010)
	Modeled harvestable yield	6.2-9.4	EU	Stampfl et al. (2007)
	1996 (drought)	3.4	Denmark	Vargas et al. (2002)
	1997	5.9		
Hybrid Poplar		3.5-5.3		Huang et al. (2009)
	Assumption	3.4-4	Lake States	
		4	MN	
	POLYSIS assumptions	4	NE	de La Torre Ugarte et al. (2003)
		3.6	Appalachian	
		4.6	Corn Belt	
		4.4	Lake States	
		4.5	Southeast	
		3.8	Southern Plains	
		3.8	Northern Plains	
		5.7	Pacific Northwest	

Table B.2.9 – Continued

Poplar	Assumption 10 year avg (best growing taxa)	5 3.7	Southern Michigan Upper Michigan	James et al. (2010) Miller & Bender (2008)
Willow	POLYSIS Assumption 10 year average (best taxa)	4.9 4.5 4. 4. 3.4	Northeast Appalachian Corn Belt Lake States Upper Michigan	de La Torre Ugarte et al. (2003) Miller & Bender (2008)
Aspen wood		0.45 (dry)	MN	Huang et al. (2009)
SRWC		5-12		BRDI (2008)
Woody biomass	Stock	4.6-39		USDA Forest Service (2003; 2005)
Wood residue	2006 average removal rate in Mississippi (lower bound)	1.1	Mississippi	USDA Forest Service Data
Yellow Pine	15 m^3/hectare/yr 12.5 m^3/hectare/yr	4.3 (2.3 – 4)[a] 3.6 (2 – 3.3)	Southern U.S. North Carolina	Cubbage et al. (2010)
Douglas Fir	14 m^3/hectare/yr 18 m^3/hectare/yr	4 (3.3) 5.1 (4.25)	Oregon North Carolina	Cubbage et al. (2010)
Sorghum	Previous Literature	16.4		Reijnders (2010)

Table B.2.10 – Interest rate

Details	Rate	Reference
	8%	Brechbill & Tyner (2008b; 2008a) Brechbill, Tyner, & Ileleji (2008)
Real discount rate (PV calc)	6.5%	de La Torre Ugarte et al. (2003)
Establishment and seeding	8%	Duffy & Nanhou (2002)
Operating expenses	9%	Duffy & Nanhou (2002)
Establishment and seeding	4%	Jain et al. (2010)
Farmer's real opportunity cost of machinery	5%	James et al. (2010)
Nominal interest rate	8%	Mooney et al. (2009)
Real discount rate	5.4%	Mooney et al. (2009)
Real Discount rate	4%	Popp & Hogan (2007)
	7.5%	Quick (2003)
	7.5%	Sokhansanj & Turhollow (2002)

Table B.2.11 – Stand length

Crop	Length	Reference
Switchgrass	10 Years	Brechbill, Tyner, & Ileleji (2008)
	10 years	de La Torre Ugarte et al. (2003)
	10 Years	Duffy & Nanhou (2002)
	10+ years	Fike et al. (2006b)
	10 years	Jain et al. (2010)
	10 years	James et al. (2010)
	10 years	Khanna (2008)
	10 years	Khanna & Dhungana (2007)
	10 years	Khanna, Dhungana, & Clifton-Brown (2008)
	10+ years	Lewandowski et al. (2003)
	10 years	Miller & Bender (2008)
	10 years 5 years[a]	Mooney et al. (2009)
	12 Years	Popp & Hogan (2007)
	20 Years	Tiffany et al. (2006)
Miscanthus	20-25 years	Lewandowski et al. (2003)
	20 years	Khanna (2008)
	20 years	Khanna & Dhungana (2007)
	20 years	Khanna, Dhungana, & Clifton-Brown (2008)
	15 years 10 years (sensitivity)	Jain et al. (2010)
	10 years	James et al. (2010)
Poplar	6-10 year	de La Torre Ugarte et al. (2003)
	10 years	James et al. (2010)
	10 year analysis	Miller & Bender (2008)
Willow	22 year	de La Torre Ugarte et al. (2003)
	10 year analysis	Miller & Bender (2008)
Yellow Pine (South US) Yellow Pine (NC)	30 23	Cubbage et al. (2010)
Douglas Fir	45	Cubbage et al. (2010)

[a] Based on the assumption that it will be optimal to replace with improved seed and contracts.

Table B.2.12 – Yield maturity rate

Type of Feedstock	Year 1	Year 2	Year 3	Reference
Switchgrass	30%	67%	100%	de La Torre Ugarte et al. (2003)
	30-100	67-100	100%	Jain et al. (2010)
	Max at 3 years			James et al. (2010)
	30%	67%	100%	Kszos et al. (2002)
	~33%	~66%	100%	McLaughlin & Kszos (2005)
	14% of 3rd year	59% of 3rd year		Mooney et al. (2009)
	0	60%	100%	Popp & Hogan (2007)
	20-35% (No harvest)	60-75%	100%	Walsh (2008)
Miscanthus	Max at 4 years	--	--	Atkinson (2009)
	2 years in warm climate 3 years in cooler climates	--	--	Clifton-Brown et al. (2001)
	2-5 years for full	--	--	Heaton et al. (2004a)
	0	40-50	100	Jain et al. (2010)
	Max at 3 years	--	--	James et al. (2010)
Willow	60% in year 4, 100% after	--	--	de La Torre Ugarte et al. (2003)
Timber	5 year establishment period	--	--	Cubbage et al. (2010)

Appendix B.3 – Summary of biomass cost estimates and assumptions

Table B.3.1 – Summary of biomass cost estimates and assumptions

Feedstock	Details	$ per ton (not updated)	Source
Alfalfa	Breakeven price	54-57	Hallam et al. (2001)
	Weighted average of leaf meal and stems	84	Vadas et al. (2008)
Alfalfa hay	3 price scenarios	80, 110, 140	Vadas et al. (2008)
Biomass	Literature summary	20-100	Busby et al. (2007)
	Maximum	49-61	de la Torre Ugarte et al. (2009)
	Delivered cost (02$)	34	Hess et al. (2007)
	Feedvalue of AFEX-treated biomass (07$)	89 (71-102.5)	Lambert & Middleton (2010)
	Marginal value to plant	19	Lambert & Middleton (2010)
	1,000-4,000 tons/day	44-58	Mapemba et al. (2007)
	Delivered cost	47	Mapemba et al. (2008)
	Feedstock production cost	65	Solomon et al. (2007)
	Supply curve range	13-50	Western Governors' Association (2008)
Corn Cobs	Range for analysis ($20 intervals)	40-120	Erickson & Tyner (2010)
Energy crops	Literature summary	25 - >115	Jenkins et al. (2009)
Grass Mix	Price assumption from literature	54	James et al. (2010)
Hay (Non-alfalfa)	06-09 Michigan average	100	James et al. (2010)
Hybrid Poplar	Production and transport	52	Gan & Smith (2006)
	Delivered Cost; cropland	85	Huang et al. (2009)
Miscanthus	Low cost scenario; farm-gate	48-139	Jain et al. (2010)
	High cost scenario; farm-gate	77-212	Jain et al. (2010)
	Price assumption from literature	54	James et al. (2010)
	Breakeven price to replace CC (current)	180 (161-198)	James et al. (2010)
	Breakeven price to replace CC (future)	42 (24-60)	James et al. (2010)
	Breakeven (low-high)	84-111	Khanna (2008)
	Breakeven	53.5	Khanna, Dhungana, & Clifton-Brown (2008)
	Breakeven	53.5	Khanna & Dhungana (2007)
	Farm Gate	60-80	Tyner et al. (2010)
Mixed Grasses	Breakeven price to replace CC	120 (40-200)	James et al. (2010)
Native Prairie	Breakeven price to replace CC	522 (189-854)	James et al. (2010)
Perennials	Competitive price	40	de La Torre Ugarte et al. (2003) and McLaughlin et al. (2002)

Table B.3.1 – Continued

Poplar	Assumption	33-44	de La Torre Ugarte et al. (2003)
	Breakeven price to replace CC	98 (60-135)	James et al. (2010)
	Price assumption from literature	54	James et al. (2010)
Prairie Mix	Price assumption from literature	54	James et al. (2010)
Reed Canarygrass	Farmgate cost; cropland	50-80	Brummer et al. (2002)
	Farmgate cost; grassland	46-72	Brummer et al. (2002)
	Breakeven price	41-67	Hallam et al. (2001)
Residue	Value as livestock feed (97$)	14-30	Gallagher et al. (2003a; 2003b)
Sorghum	Observed commody price (07$)	145	Chen et al. (2010)
	Modeled price (2007$)	131	Chen et al. (2010)
	Value as livestock feed (97$)	43	Gallagher et al. (2003a; 2003b)
	Breakeven price; forage	30-38	Hallam et al. (2001)
	Production cost (Florida); silage	50-90	Hewitt (2006)
	Mean assumption; silage	64	Rahmani & Hodges (2006)
Stover	07$ cost assumption	46	Aden (2008)
	02$ cost assumption	30	Aden et al. (2002)
	Produce, store and transport 30 miles	39-46	Brechbill & Tyner (2008a)
	Average production and transport by farm size and equipment	36-49	Brechbill & Tyner (2008b)
	Assumption (07$)	30	Carolan et al. (2007)
	Average cost to deliver (06$)	89	U.S. EPA (2009)
	Value as livestock feed (97$)	42	Gallagher et al. (2003a; 2003b)
		35	Glassner et al (1998)
	Farmer payments	9.3-38/acre	Glassner et al (1998)
	Fieldedge (02$)	30	Graham et al. (2007)
	Fieldside cost (02$)	25-40	Graham et al. (2007)
	Delivered cost	51	Huang et al. (2009)
	Stored and delivered Baseline Sensitivity range	 75 50-100	Kazi et al. (2010b)
	Breakeven (low-high)	83-101	Khanna (2008)
	77-01 mean crop price	29	Larson et al. (2005)
	Assumption	35	McAllon et al. (2000)
	Collect, store, haul	44-49	Perlack & Turhollow (2002)
	Collect, store, haul (conventional baling)	43-53	Perlack & Turhollow (2003)
	Marginal feedstock cost (refinery)	54-84	Petrolia (2008)
	Mean marginal feedstocks cost	52	Petrolia (2008)

Table B.3.1 – Continued

Stover (continued)	First plant to last 10 plants	42-60	Sheehan et al. (2004)
	Delivered cost (bales - chopped)	66-76	Sokhansanj et al. (2010)
	Farm Gate	50-70	Tyner et al. (2010)
	Assumed delivered prices	20, 30, 40	Vadas et al. (2008)
		40	Wallace et al. (2005)
Straw	Competing use value	45-50	Banowetz et al. (2008)
	Delivered value in Idaho dairy market (max)	32-42 (max: 60)	Grant et al. (2006)
	Delivered value (04$)	32-42	Hess et al. (2007)
	Price to grower (quality and supply)	28-60	Hess et al. (2007)
	Supplied to biorefinery	40	Leistritz et al. (2006)
Switchgrass	Breakeven revenue	82-110	Babcock et al. (2007)
	Processor willingness	38	Babcock et al. (2007)
	Long-run results under varying scenarios	141-165	Baker et al. (2008)
	Production cost - ND	47-76	Bangsund et al. (2008)
	Produce, store and transport 30 miles	57-63	Brechbill & Tyner (2008a)
	Average production and transport by farm size and equipment	58-71	Brechbill & Tyner (2008b)
	Cropland; range (no storage to collective storage)	76-101	Brummer et al. (2002)
	Grassland; range (no storage to collective storage)	69-95	Brummer et al. (2002)
	Assumption (07$)	30	Carolan et al. (2007)
	Production cost - Missouri	86	Carpenter & Brees (2008)
	Virginia	46-53.5	Cundiff & Harris (1995)
	Assumption	30-40	de La Torre Ugarte et al. (2003)
	Production cost - IA	114	Duffy (2007)
	Range based on assumptions	54-149	Duffy & Nanhou (2002)
	Iowa scenarios	54-149	Duffy & Nanhou (2002)
	Delivered cost (9 month season) Delivered cost (2 month season)	52.3 64.3	Epplin & Haque (2011)
	Farmgate cost - TN	36-52	Epplin et al. (2007)
	Delivered cost - TN	49-64	Epplin et al. (2007)
	Literature review	27	Fox et al. (1999)

Table B.3.1 – Continued

Switchgrass (continued)	Average SG production cost (10 years)	24.5-33	Fox et al. (1999)
	Avareage SG production cost (20 years)	23-31	Fox et al. (1999)
	Price use hardwood fiber value	66-82.5	Fox et al. (1999)
	Production cost (Canada)	34.5-46	Girouard et al. (1999)
	North Central region	47-51	Graham et al. (1995)
	Production cost - NC (w/o establishment)	61	Green & Benson (2008)
	Breakeven price	28-34	Hallam et al. (2001)
	Cropland; Delivered cost	81	Huang et al. (2009)
	Grassland; delivered cost	70	Huang et al. (2009)
	Low cost scenario; farm-gate	80-131	Jain et al. (2010)
	High cost scenario; farm-gate	107-170.5	Jain et al. (2010)
	Breakeven price to replace CC	104 (41-167)	James et al. (2010)
	Price assumption from literature	54	James et al. (2010)
	Supplier breakeven range	82.5-486	Jiang & Swinton (2008)
	Processor breakeven range	17-57	Jiang & Swinton (2008)
	Breakeven (low-high)	230-252	Khanna (2008)
	Breakeven	89	Khanna & Dhungana (2007)
	Farmgate breakeven (annualized)	89	Khanna, Dhungana, & Clifton-Brown (2008)
	Farmgate price assumpton	35	Kszos et al. (2002)
	Delivered (does NOT include farming cost or extra payment)	33.5-43.5	Kumar & Sokhansanj (2007)
	77-01 mean crop price	30	Larson et al. (2005)
	Farmgate price - delivered	40	McLaughlin & Kszos (2005)
	Delivered price	49	McLaughlin & Kszos (2005)
	Assumptions for POLYSIS	27-47	McLaughlin et al. (2002)
	Assumptions (2013 & 2025)	30-60	McLaughlin et al. (2006)
	Tennessee - 04$	53	Mooney et al. (2009)
	Literature review	36-116	Mooney et al. (2009)
	Price to supply 70 MGY plant	100	Mooney et al. (2009)
	Price needed to jump-start supply	60	Mooney et al. (2009)
	Scenarios	30, 35, 50	Morrow et al. (2006)
	Fieldside breakeven cost; Kansas	23-37	Nelson et al. (2006)

Table B.3.1 – Continued

Switchgrass (continued)	Production cost - ND, SD, NE, OK	42-71	Perrin et al. (2008)
	Average production cost (5 years, 10 sites)	60	Perrin et al. (2008)
	Production cost including transport and storage loss	53-61	Popp & Hogan (2007)
	NPV	136/acre	Song et al. (2011)
	Farm gate	65-85	Tyner et al. (2010)
	3 assumed delivered prices	30, 60, 90	Vadas et al. (2008)
	Midwest	30-70	Wright et al. (2000) - cited in Jenkins et al. (2009)
Switchgrass & Big bluestem	Iowa (93$)	55	Hallam et al. (2001)
Wheat	Observed commodity price (07$)	197	Chen et al. (2010)
	Model (07$)	217	Chen et al. (2010)
	Different scenarios and year	5.9-7.6/bu	de la Torre Ugarte et al. (2009)
	Baseline to long-run solution	3.8-4.6/bu	Elobeid et al. (2006)
	Value as livestock feed (97$)	21	Gallagher et al. (2003a; 2003b)
	97-07 County-level average	4.20/bu	Huang & Khanna (2010)
	97-07 County-level range	1.80-8.60/bu	Huang & Khanna (2010)
Wheat Straw	Delivered to 20 MGY plant	32-53.5	Kerstetter & Lyons (2001)
	77-01 mean crop price	27	Larson et al. (2005)
Willow	Assumption	32-42	de La Torre Ugarte et al. (2003)
Wood	Waste	10-20	BRDI (2008)
	Harwood; Assumed price at mill	72.5-91	Fox et al. (1999)
	Delivered cost (Aspen)	83	Huang et al. (2009)
	Forest thinning and stand improvement	30-50	Jenkins et al. (2009)
	Assumption	31	Perez-Verdin et al. (2009)
	Delivered cost	34-65	Sohngen et al. (2010)
	Short-run woody crops	50-60	Tyner et al. (2010)
	Forest residues	45	Tyner et al. (2010)
	Gross cost range (forest biomass)	36 to >1000/acre	USDA Forest Service (2003; 2005)
	Raw materials cost	42	Wyman (1999)

Appendix B.4 – Graphical depiction of the costs and revenues from a cellulosic biofuel blend mandate

The biofuel mandate results in a direct increase in cost to consumers equal to $(P_M Q_M - P_{NM} Q_{NM})$. This cost is represented by the difference in areas $P_{NM} - P_M - C - E$ and $Q_M - E - D - Q_{NM}$ as depicted in Figure B.4.1. This cost is equivalent to the total (net) gain in revenues to all fuel producers. Cellulosic biofuel producers experience an increase in revenues of $Q_{CB}^M P_{CB}^M$ equal to the area $O - P_{CB}^M - A - Q_{CB}^M$ in Figure B.4.2 while conventional fuel producers have revenue losses equal to $P_{NM} Q_{NM} - P_F^M Q_F^M$ depicted by sum of areas $P_F^M - P_{NM} - G - F$ and $Q_F^M - G - D - Q_{NM}$ in Figure B.4.3.

Figure B.4.1 - Additional cost to fuel consumers from cellulosic biofuel blend mandate (α)

(Box 1 minus Box 2)

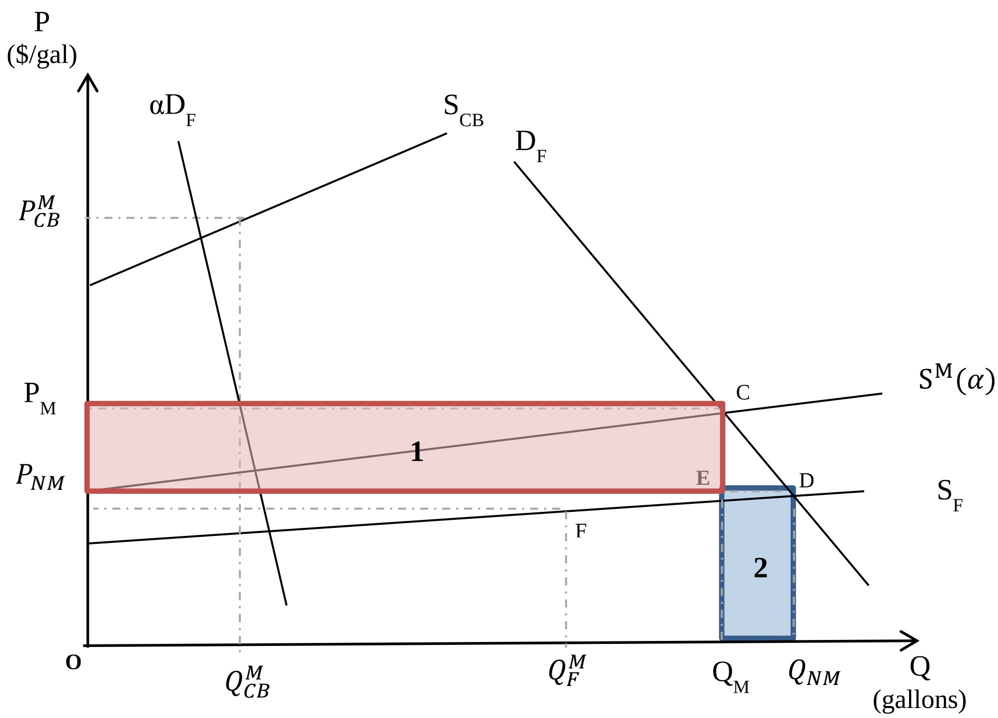


Figure B.4.2 – Additional revenue to biofuel producers from cellulosic biofuel blend mandate (α)

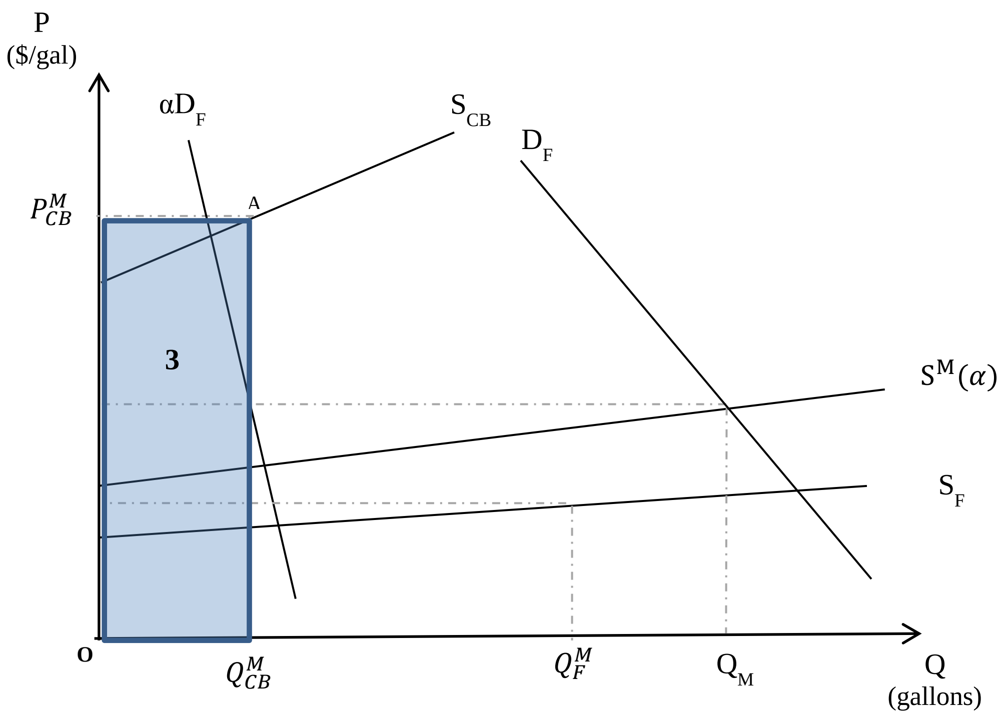
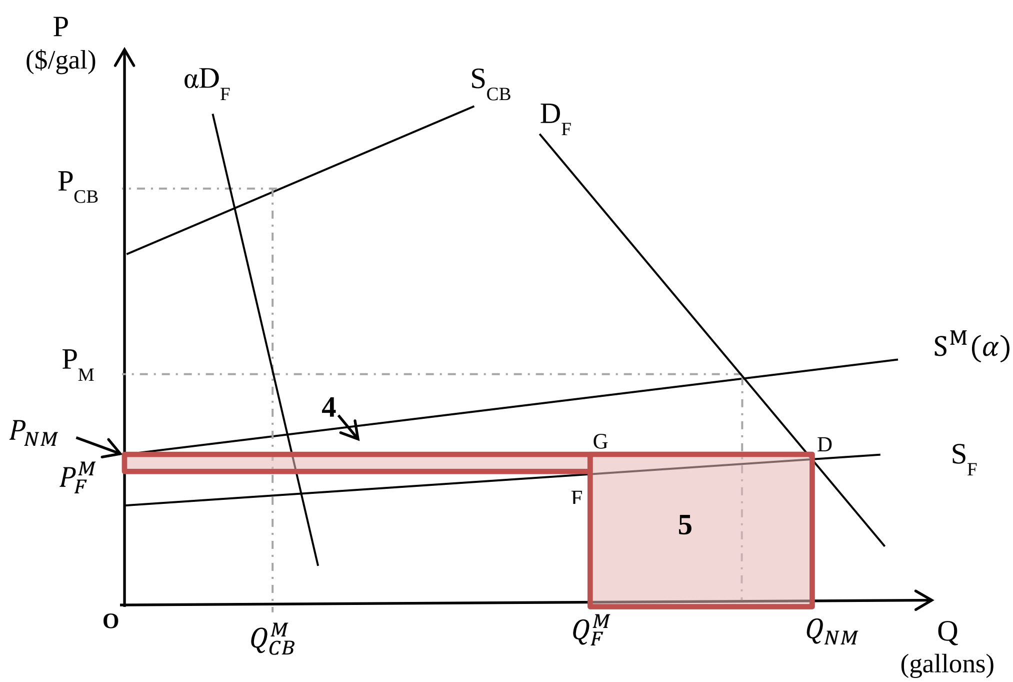


Figure B.4.3 – Lost revenue to conventional fuel producers from cellulosic biofuel blend mandate (α)
(Box 4 plus Box 5)



APPENDIX C. ADDITIONAL MATERIAL FOR CHAPTER 4

Appendix C.1 – Conditions for a convex objective function

This section derives conditions for convexity of the biorefinery objective function. The biorefinery objective function (equation 7 in the main text) is written as follows:

$$\min_{Q,P_F} \; C(Q,P_F) = \min_{Q,P_F} \; C_{P,N} + C_{P,Q_0} \times \left[\frac{Q}{Q_0}\right]^{k-1} + \frac{1}{Y_O} \times \left[P_F + S + t \times \gamma \times \sqrt{\frac{Q}{Y_O \times Y_B \times d(P_F)}}\right]$$

where $\frac{\partial d(P_F)}{\partial P_F} \geq 0$

$d(P_F) \in [0, 1]$

$Q, P_F \geq 0$

First-order necessary conditions for an interior solution include:

$$\frac{\partial C}{\partial Q} = \frac{(k-1)C_{P,Q_0}}{Q_0^{k-1}} Q^{*k-2} + \frac{t\gamma}{2Y_O\sqrt{Y_O Y_B d(P_F)}} Q^{*-\frac{1}{2}} = 0 \qquad \text{(FOC 1)}$$

$$\frac{\partial C}{\partial P_B} = \frac{1}{Y_O}\left[1 - \frac{t\gamma}{2}\sqrt{\frac{Q^*}{Y_O \times Y_B}} * \frac{\partial d(P_F^*)}{\partial P_F} * d(P_F^*)^{-\frac{3}{2}}\right] = 0. \qquad \text{(FOC 2)}$$

The second-order sufficient conditions for strict local minima (i.e., strict convexity) require the Hessian matrix to be positive definite. To test for positive definiteness, we derive the leading principle minors of the Hessian matrix, denoted as H. The necessary-and-sufficient conditions for positive definiteness require strictly positive leading principle minors or

(1). $H_{11} > 0$ and

(2). $H_{11}H_{22} - H_{12}^2 > 0$

where H_{ij} denotes element (i, j) of Hessian matrix. The corresponding elements of the Hessian matrix for the biorefinery objective function are

$$H_{11} = \frac{\partial^2 C}{\partial Q^2} = \frac{(k-1)(k-2)C_{P,Q_0}}{Q_0^{k-1}} Q^{*k-3} - \frac{1}{4Y_O}\frac{t\gamma}{\sqrt{Y_O Y_B d(P_F)}} Q^{*-\frac{3}{2}}$$

$$H_{22} = \frac{\partial^2 C}{\partial P_F^2} = \frac{-t\gamma}{2Y_O}\sqrt{\frac{Q}{Y_O Y_B}}\left[\frac{\partial^2 d(P_F)}{\partial P_F^2} d(P_F)^{-\frac{3}{2}} - \frac{3}{2}\left(\frac{\partial d(P_F)}{\partial P_F}\right)^2 d(P_F)^{-\frac{5}{2}}\right]$$

$$H_{12} = H_{21} = \frac{\partial^2 C}{\partial Q \partial P_F} = \frac{\partial^2 C}{\partial P_F \partial Q} = \frac{-t \times \gamma \times \frac{\partial d(P_F)}{\partial P_F}}{4 \times Y_O \times \sqrt{Y_O \times Y_B \times Q \times d^3}}.$$

The first condition for convexity requires $H_{11} > 0$, which leads to the following relationship:

$$H_{11} > 0 \quad \leftrightarrow \quad Q^{k-\frac{3}{2}} > \frac{t\gamma Q_0^{k-1}}{4(k-1)(k-2)Y_O C_{P,Q_O}\sqrt{Y_O Y_B d(P_F)}}$$

$$\leftrightarrow Q < \left(\frac{t\gamma Q_0^{k-1}}{4(k-1)(k-2)Y_O C_{P,Q_O}\sqrt{Y_O Y_B d(P_F)}}\right)^{\frac{1}{k-1.5}}.$$

The direction of the inequality is reversed in the last equation since both sides are raised to a negative power (that is, $\frac{1}{k-1.5} < 0$).

The second condition for convexity requires $H_{11}H_{22} - H_{12}^2 > 0$. With some algebra and the equations above, this requirement can be written as follows:

$$\boldsymbol{H_{11}H_{22} - H_{12}} = \left[\frac{3}{2d(P_F)}\left(\frac{\partial d(P_F)}{\partial P_F}\right)^2 - \frac{\partial^2 d(P_F)}{\partial P_F^2}\right]\left(\frac{(k-1)(k-2)t\gamma C_{P,Q_0} Q^{k-\frac{3}{2}}}{2Q_0^{k-1}\sqrt{Y_O^3 Y_B d(P_F)^3}}\right) - \frac{\partial^2 d(P_F)}{\partial P_F^2}\left(\frac{t^2\gamma^2}{8Y_O^3 Y_B Q d(P_F)^2}\right) + \left(\frac{t^2\gamma^2\left(\frac{\partial d(P_F)}{\partial P_F}\right)^2}{8Y_O^3 Y_B Q d(P_F)^3}\right) > 0$$

Rearranging, the second (sufficient and necessary) condition for the biorefinery objective function to be strictly convex requires:

$$\Bigg[\underbrace{\frac{3}{2d(P_F)}\left(\frac{\partial d(P_F)}{\partial P_F}\right)^2}_{(+)} - \underbrace{\frac{\partial^2 d(P_F)}{\partial P_F^2}}_{?}\Bigg] > \Bigg[\underbrace{\frac{\partial^2 d(P_F)}{\partial P_F^2}}_{?} - \underbrace{\frac{1}{d(P_F)}\left(\frac{\partial d(P_F)}{\partial P_F}\right)^2}_{(+)}\Bigg]\underbrace{\left(\frac{t\gamma Q_0^{k-1}}{4(k-1)(k-2)C_{P,Q_0} Q^{k-\frac{1}{2}}\sqrt{Y_O^3 Y_B d(P_F)}}\right)}_{\text{'A' } (+)}.$$

This inequality will hold for: $\frac{\partial^2 d(P_F)}{\partial P_F^2} < \underbrace{\frac{(3+2A)}{(2+2A)d(P_F)}}_{(+)}\left(\frac{\partial d(P_F)}{\partial P_F}\right)^2.$

Therefore, the sufficient-and-necessary conditions for strict local minima to the biorefinery objective function require the following:

1. $Q^* < \left(\frac{t\gamma Q_0^{k-1}}{4(k-1)(k-2)Y_O C_{P,Q_O} \sqrt{Y_O Y_B d(P_F^*)}} \right)^{\frac{1}{k-1.5}}$ and

2. $\frac{\partial^2 d(P_F^*)}{\partial P_F^{*2}} < \frac{(3+2A)}{(2+2A)d(P_F^*)} \left(\frac{\partial d(P_F^*)}{\partial P_F^*} \right)^2$.

Given the parameter assumptions used in the application to switchgrass-based ethanol production, these conditions hold for all potential biorefinery locations.

Appendix C.2 – Derivation of cost-minimizing capacity and price of feedstock function

This section derives the first-order condition for the biorefinery optimization problem presented in the main text (equation 8). Recall, the biorefinery objective function:

$$\min_{Q,P_F} \; C(Q,P_F) = \min_{Q,P_F} \; C_{P,N} + C_{P,Q_0} \times \left[\frac{Q}{Q_0}\right]^{k-1} + \frac{1}{Y_O} \times \left[P_F + S + t \times \gamma \times \sqrt{\frac{Q}{Y_O \times Y_B \times d(P_F)}}\right]$$

$$\text{where} \qquad \frac{\partial d(P_F)}{\partial P_F} \geq 0$$

$$d(P_F) \in [0,1]$$

$$Q, P_F \geq 0.$$

First-order necessary conditions for an interior solution to the biorefinery object function include:

$$\frac{\partial C}{\partial Q} = \frac{C_{P,Q_0}}{Q_0^{k-1}}(k-1)Q^{*k-2} + \frac{1}{Y_O}\frac{t \times \gamma}{\sqrt{Y_O \times Y_B \times d(P_F)}}\frac{1}{2}Q^{*-\frac{1}{2}} = 0 \qquad \text{FOC (1)}$$

$$\frac{\partial C}{\partial P_B} = \frac{1}{Y_O}\left[1 - \frac{t \times \gamma}{2}\sqrt{\frac{Q^*}{Y_O \times Y_B}} \times \frac{\partial d(P_F^*)}{\partial P_F} \times d(P_F^*)^{-\frac{3}{2}}\right] = 0 \qquad \text{FOC (2)}$$

Rearranging FOC (1) to solve for Q and FOC (2) to solve for $d(P_F^*)$, the two first-order conditions can be rewritten as:

$$Q^* = \left[\frac{2 \times C_{P,Q_0} \times (1-k) \times \sqrt{Y_O^3 \times Y_B \times d(P_F^*)}}{t \times \gamma \times Q_0^{k-1}}\right]^{\frac{2}{3-2k}} \qquad \text{FOC (1)'}$$

$$d(P_F^*) = \left[\frac{t \times \gamma}{2}\sqrt{\frac{Q^*}{Y_O \times Y_B}} \times \frac{\partial d(P_F^*)}{\partial P_F}\right]^{\frac{2}{3}}. \qquad \text{FOC (2)'}$$

Substituting FOC (2)' into FOC (1)' yields the following

$$Q^* = \left[\frac{2 \times C_{P,Q_0} \times (1-k)\sqrt{Y_O^3 \times Y_B}}{t \times \gamma \times Q_0^{k-1}}\right]^{\frac{2}{3-2k}} \left[\frac{t \times \gamma}{2}\sqrt{\frac{1}{Y_O \times Y_B}} \times \frac{\partial d(P_F^*)}{\partial P_F}\right]^{\frac{2}{3(3-2k)}} \times Q^{*\frac{1}{3(3-2k)}}.$$

Solving for Q^* results in the following equation for minimum efficient capacity and cost-minimizing price of feedstock, or equation 8 in the Chapter 4:

$$Q^* = \left[\frac{\partial d(P_F^*)}{\partial P_F} \times \frac{4 \times C_{P,Q_0}^3 \times (1-k)^3 \times Y_O^4 \times Y_B}{t^2 \times \gamma^2 \times Q_0^{3(k-1)}}\right]^{\frac{1}{4-3k}}.$$

Appendix C.3 – Biorefinery objective function with fixed density and price of biomass

The biorefinery objective function with a fixed density (d_{fixed}) and price of biomass ($P_{F,fixed}$) can be written as:

$$\min_Q C(Q) = \min_Q \; C_{P,N} + C_{P,Q_0} \times \left[\frac{Q}{Q_0}\right]^{k-1} + \frac{1}{Y_O} \times \left[P_{F,fixed} + S + t \times \gamma \times \sqrt{\frac{Q}{Y_O \times Y_B \times d_{fixed}}}\right].$$

The first-order condition for an interior solution can be written as:

$$\frac{\partial C}{\partial Q} = \frac{C_{P,Q_0}}{Q_0^{k-1}}(k-1)Q^{*k-2} + \frac{1}{Y_O}\frac{t * \gamma}{\sqrt{Y_O * Y_B * d_{fixed}}}\frac{1}{2}Q^{*-\frac{1}{2}} = 0.$$

Solving for the minimum efficient capacity (Q^*) results in

$$Q^*_{fixed\ d} = \left[\frac{2 \times C_{P,Q_0} \times (1-k) \times \sqrt{Y_O^3 \times Y_B \times d_{fixed}}}{t \times \gamma \times Q_0^{k-1}}\right]^{\frac{2}{3-2k}}$$

with corresponding capture radius equal to

$$r^*_{fixed\ d} = \gamma \sqrt{\frac{Q^*_{fixed\ d}}{Y_O \times Y_B \times d_{fixed}}}.$$

The solution to the biorefinery's objective function is a minimum efficient capacity that is independent of the fixed price of biomass ($P_{F,fixed}$). The resulting capture radius is also independent of $P_{F,fixed}$. Yet, the cost-minimizing biorefinery capacity and capture radius depend on the assumed density value with capacity increasing and radius decreasing in d_{fixed}. Table C.3.1 contains a summary of the marginal impact of select model parameters on optimal biorefinery capacity and capture radius with a fixed price and density of biomass.

Table C.3.1 – Marginal impacts with fixed density and feedstock price

	$Q^{*}_{fixed\ d}$	$r^{*}_{fixed\ d}$	**Intuition**
$P_{F,fixed}$	None	None	--
k	Decreasing	Decreasing	The degree of economies of scale is inversely related to the economies of scale factor (k). The minimum efficient capacity decreases as the economies of scale decrease holding the diseconomies of transportation constant.
C_{P,Q_0}	Increasing	Increasing	The benefits from economies of scale increase as the per gallon baseline costs that exhibit economies of scale increase.
t	Decreasing	Decreasing	The minimum efficient capacity decreases as the diseconomies of biomass transportation increase holding economies of scale in biorefinery production constant.
Y_b	Increasing	Decreasing	All else constant, the capture radius to meet a given feedstock demand decreases as yield increases. The transportation cost decreases, resulting in an increase in minimum efficient capacity.
d_{fixed}	Increasing	Decreasing	The capture radius to meet a given feedstock demand decreases as density increases, holding all else equal. The transportation cost decreases, resulting in an increase in minimum efficient capacity.

Figure C.4.1 – Switchgrass production cost for each CRD in the rain-fed region with at least 20 offers
(Source: Khanna et al., 2011 adjusted for yield assumptions)

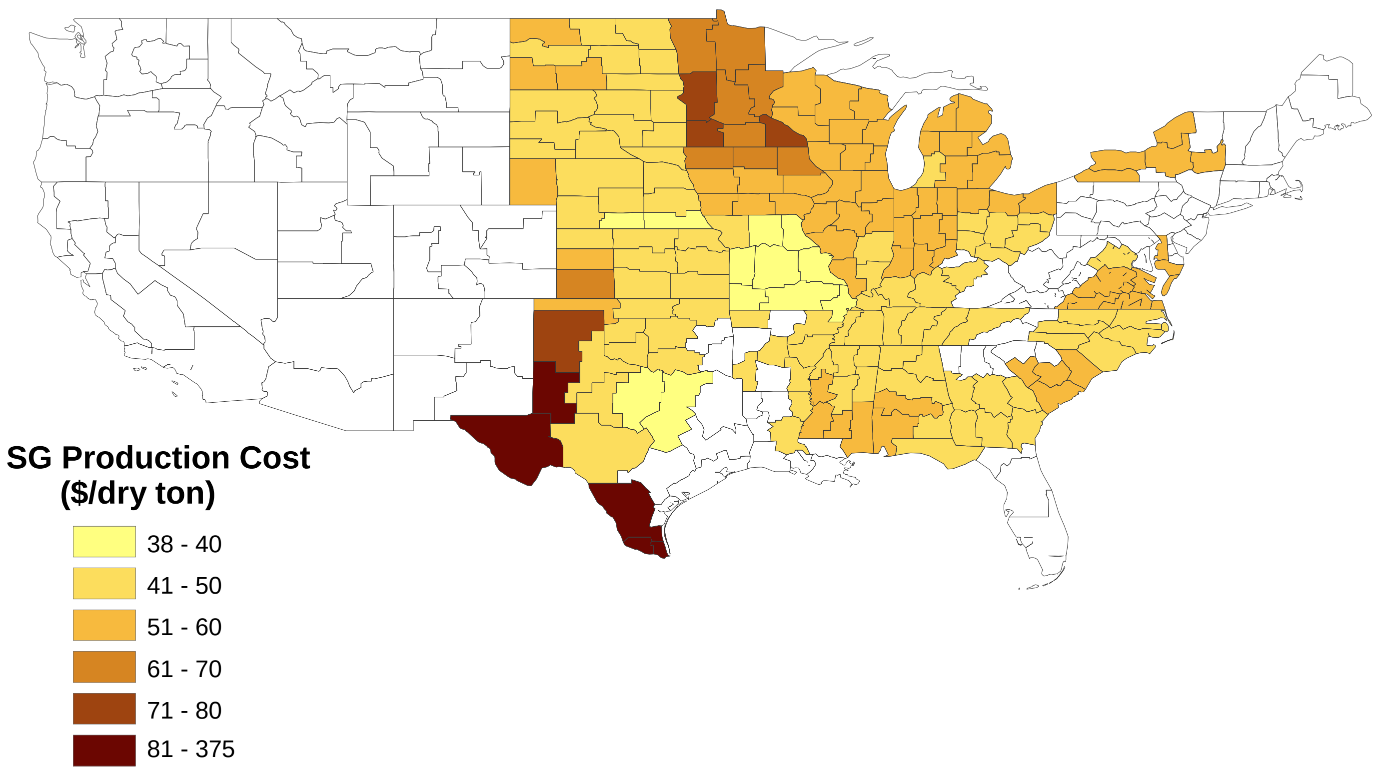


Figure C.4.2 – Switchgrass yield for each CRD in the rain-fed region with at least 20 offers
(Source: 75% of value reported by Khanna et al., 2011)

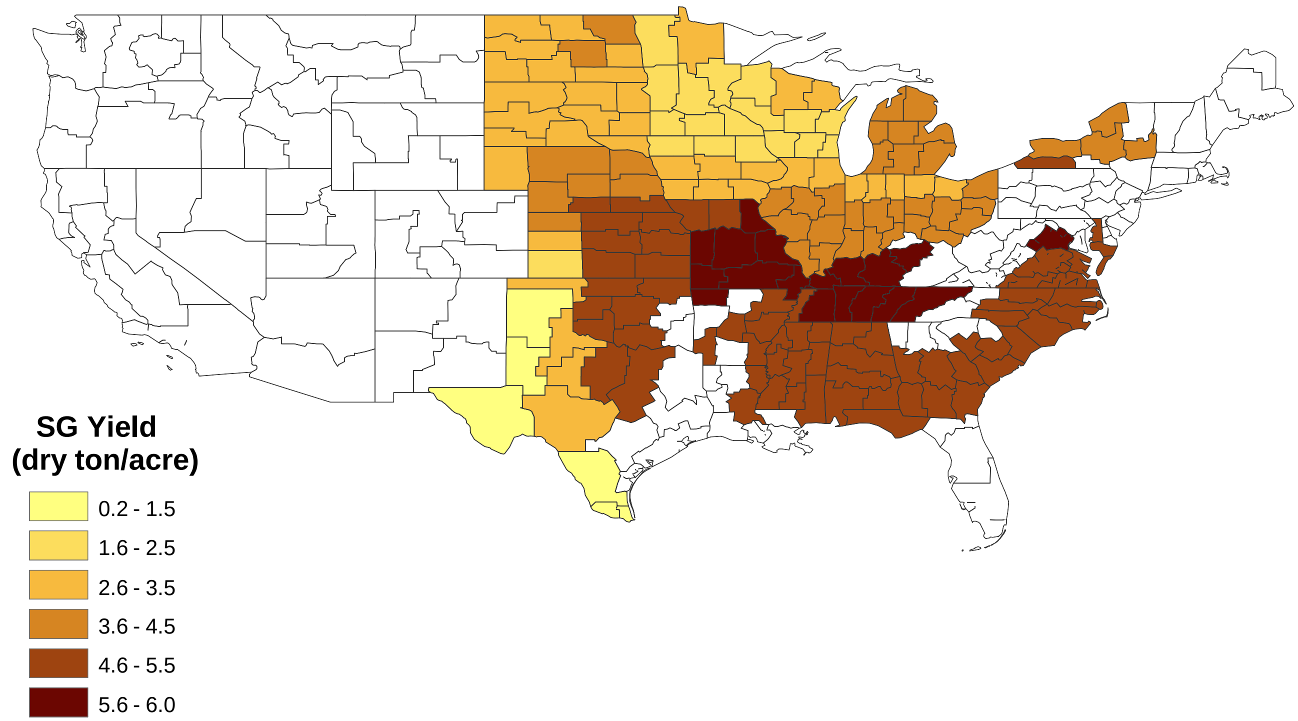


Figure C.4.3 – Biorefinery minimum efficient capacity by CRD

(Numbers identify the 10 biorefinery locations with lowest per gallon cost where 1 represents the least cost location)

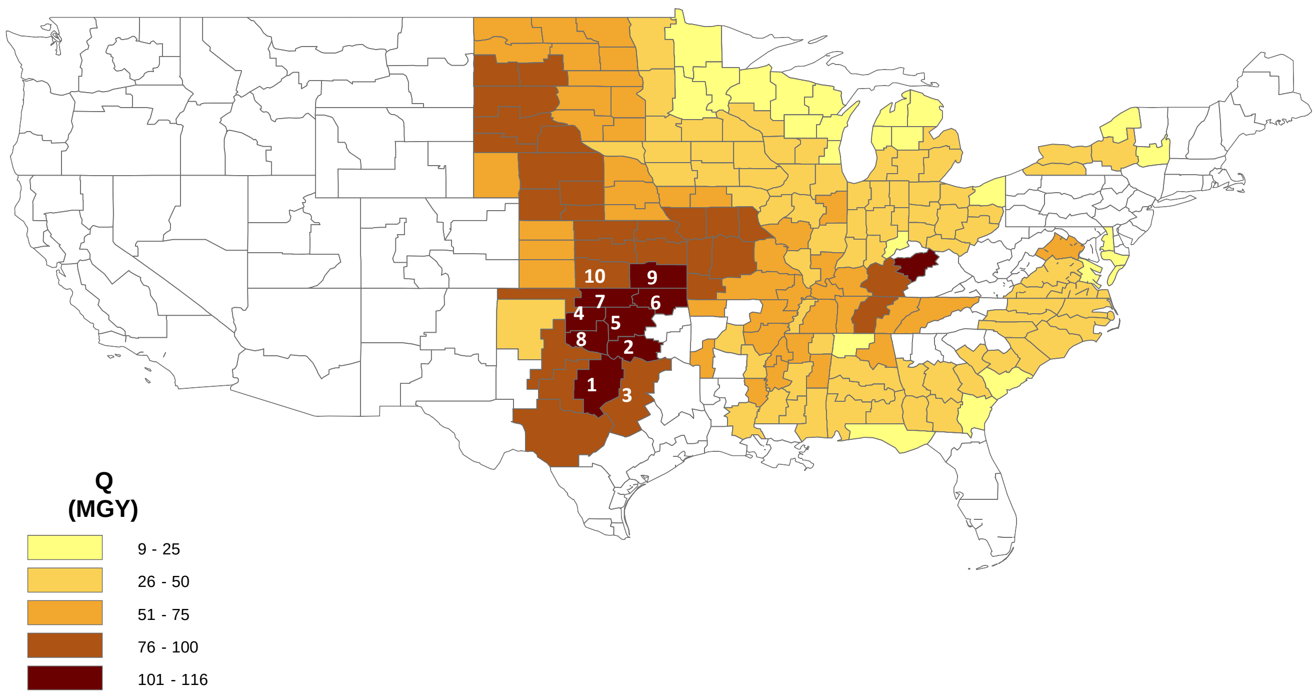


Figure C.4.4 – Breakeven biofuel production with long run price of oil

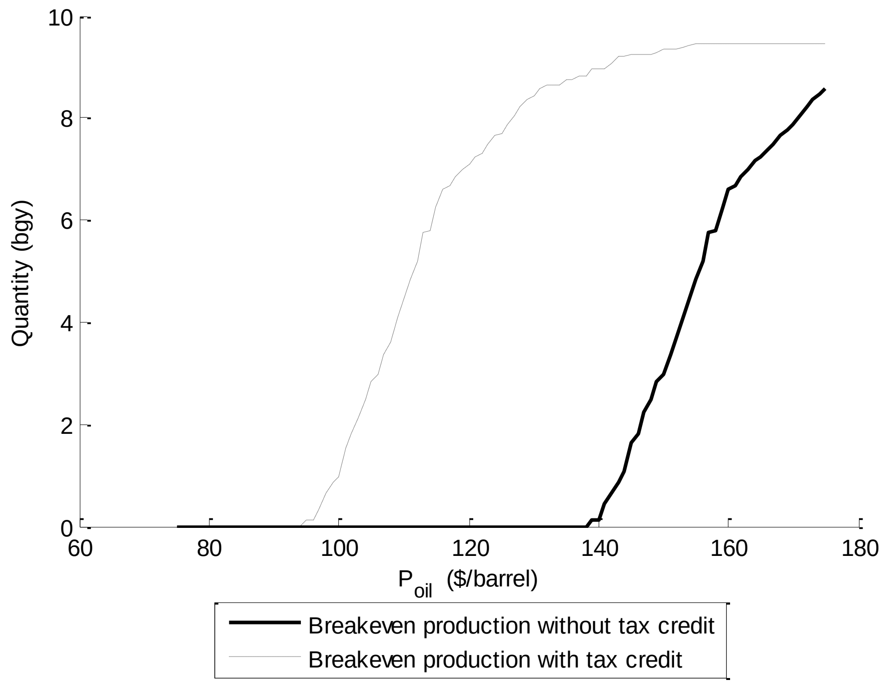


Figure C.4.5 – Estimated aggregate ethanol supply curve with and without acreage constraint

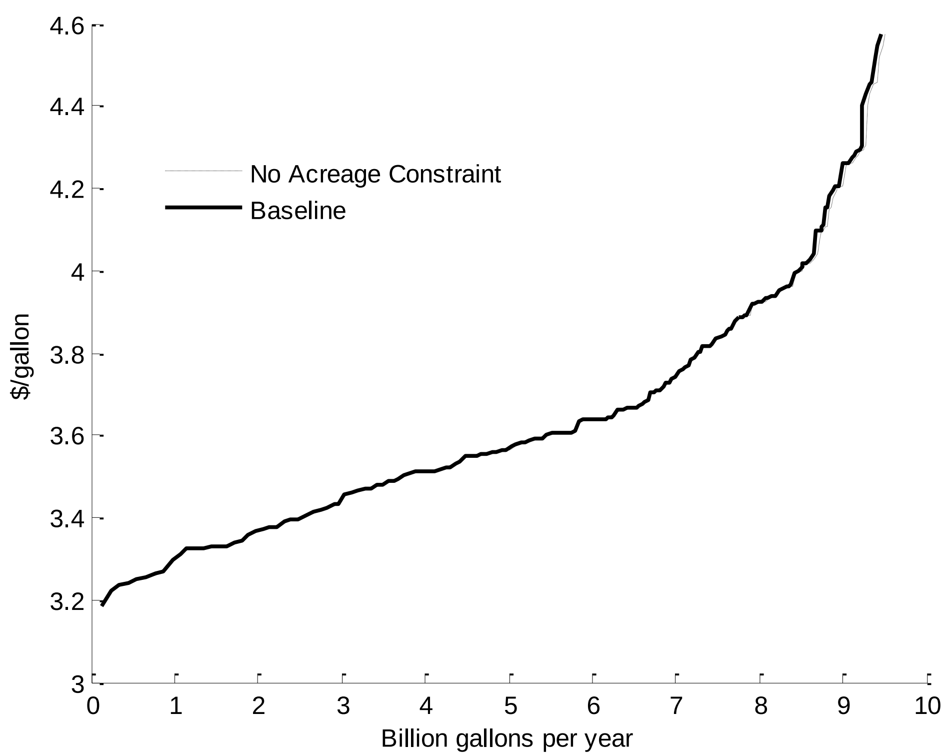
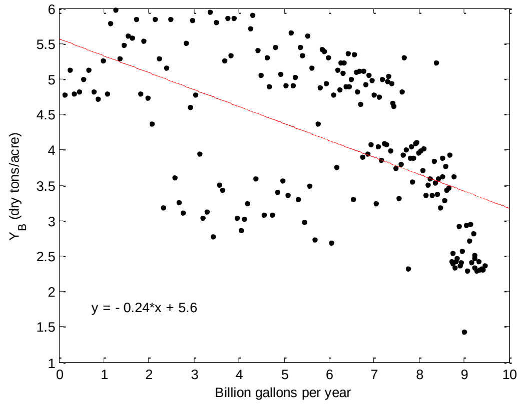
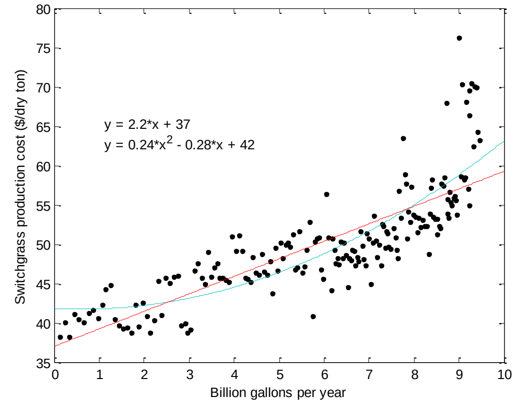


Figure C.4.6 – Biorefinery characteristics along the aggregate supply curve

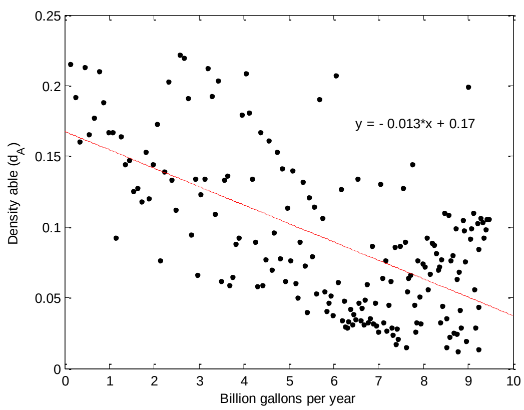
(a). Biomass yield (Y_B)



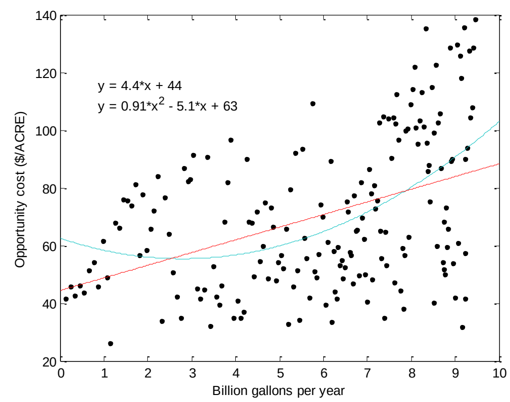
(b). Switchgrass production cost (P_{SG})



(c). Available land (d_A)



(d). Opportunity cost per acre (P_{Opp})



(e). Opportunity cost per ton (P_{Opp}/Y_B)

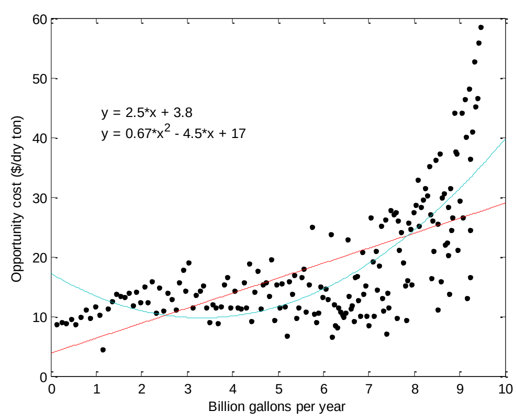


Table C.4.1 – Average difference in cost-minimizing decisions between alternative assumptions and baseline results[a]
(All 182 CRDs)

	Aggregate Capacity	Average difference from baseline (182 CRDs)[a]				
	$Q_T - Q_{T,base}$ (bgy)	Q (mgy)	r (miles)	d_S	$\frac{P_{Opp}}{Y_B}$ ($/dt)	C ($/gallon)
Low Y_B (60% Khanna et al.)	-1.5	-8 (-20,-2)	1 (0,3)	-3% (-27,0)	4.1 (0,12)	0.29 (0.2,0.5)
High Y_B (100% Khanna et al.)	2	11 (0,25)	-2 (-5,0)	2% (-7,19)	-4 (-13,-1)	-0.30 (-0.5,-0.2)
Low d_A (60% willing to consider)	-2.9	-16 (-36,-3)	2 (0,5)	1% (-16,15)	0 (-3,2)	0.10 (0.1,0.2)
High d_A	2.6	14 (0,41)	-4 (-12,0)	-2% (-27,14)	0 (-6,2)	-0.09 (-0.2,0)
Low t (t = 0.50)	4.1	22 (-2,70)	6 (0,12)	-1% (-7,14)	0 (-1,2)	-0.12 (-0.2,-0.1)
High t (t = 1.00)	-3.3	-18 (-45,0)	-7 (-11,0)	1% (-16,16)	0 (-3,3)	0.13 (0.1,0.2)
Low k (k = 0.60)	4.5	25 (0,58)	6 (0,16)	4% (-1,21)	1 (0,5)	0.01 (-0.1,0.3)
High k (k = 0.90)	-7.5	-41 (-89,-5)	-18 (-32,-6)	-12% (-58,14)	-2 (-12,2)	-0.10 (-0.3,0)
Fast Pyrolysis	2.0	11 (0,27)	3 (0,5)	0% (-6,14)	0 (-2,2)	-0.96 (-1,-0.9)

[a] The average difference in a biorefinery characteristic is calculated by taking the average of the difference between the alternative model result and baseline model result across all biorefineries [i.e., Average difference in characteristic = $\frac{1}{182}\sum_{j=1:182}\left(Char_{j,alternative\ model} - Char_{j,baseline}\right)$]. That is, we calculate the average of the differences as opposed to the difference of the averages. Appendix Table C.4.2 provides analogous results for the 10 biorefinery locations with the lowest biofuel production cost per gallon.

Table C.4.2 – Average difference in cost-minimizing decisions between alternative assumptions and baseline results for the 10 least-cost locations

(10 least-cost locations only)

	$Q_T - Q_{T,base}$ (bgy)	Q (mgy)	r (miles)	d_S	$\frac{P_{Opp}}{Y_B}$ ($/dt)	C ($/gallon)
Low Y_B (60% Khanna et al.)	-0.2	-16	1	-2%	2	0.21
High Y_B (100% Khanna et al.)	0.2	23	-1	1%	-2	-0.22
Low d_A (60% willing to consider)	-0.3	-31	3	-1%	0	0.08
High d_A (50% permanent past)	0.2	17	-1	-1%	0	-0.03
Low t (t = 0.50)	0.6	63	8	-1%	0	-0.10
High t (t = 1.00)	-0.4	-40	-6	-1%	0	0.11
Low k (k = 0.60)	0.5	54	7	1%	0	-0.07
High k (k = 0.90)	-0.8	-78	-15	-3%	0	0.01
Fast Pyrolysis	0.2	24	3	-1%	0	-0.90

Table C.4.3 – Summary statistics of cost-minimizing biorefinery decisions under alternative biomass transportation models

	Q (mgy)	r (miles)	d_S @ radius	d_S @ ½ radius	d_S @ plant	$\frac{P_{Opp}}{Y_B}$ ($/dt)	C ($/gallon)	Q_T
All biorefineries (182) - Average								
Baseline	52	35	90.7%	--	--	18.6	3.73	9.4
Diminishing participation	55	37	70%	96%	99%	16.8	3.71	10
Average hauling distance	62	38	90%	--	--	18.5	3.67	11.3
All biorefineries (182) - Range								
Baseline	9 – 117	22 – 51	47 – 100%	--	--	4 – 58	3.19 – 4.57	--
Diminishing participation	9 – 131	22 – 55	29 – 93%	66 – 100%	84 – 100%	4 – 53	3.18 – 4.52	--
Average hauling distance	9 – 144	22 – 52	46 – 100%	--	--	4 – 58	3.14 – 4.51	--
Top 25% of biorefineries (average)								
Baseline	86	31	96 %	--	--	12.3	3.38	41%
Diminishing participation	90	32	76%	99%	100%	11	3.37	41%
Average hauling distance	107	35	95.3%	--	--	12.2	3.33	42%
Bottom 25% of biorefineries (average)								
Baseline	31	38	80%	--	--	31	4.17	15%
Diminishing participation	33	40	57%	88%	97%	28	4.13	15%
Average hauling distance	35	41	79%	--	--	31	4.10	14%

Appendix C.5 – Sensitivity of model results to land use constraint

Baseline results assume a fixed amount of land is available for biomass production (d_A) at heterogeneous opportunity costs as proxied by offers to enroll in the CRP. In the following, we consider two potential deviations from the land assumptions in the baseline model.

Pastureland only option

If pastureland is available at a lower opportunity cost relative to marginal cropland (i.e., rental pasture rate below CRP payments), a biorefinery located in an area with enough pasture land may find it cost-efficient to offer a high enough biomass price to incentivize pastureland into switchgrass production but not high enough to compete with cropland acreage. To evaluate the impacts on the estimated supply curve when pastureland has a different opportunity cost than marginal cropland, we make the following assumptions:

- Baseline acreage from pastureland (25%) and cropland pasture (25%) is available at an opportunity cost equal to the CRD average pasture rental rate. Landowners are assumed to require a 15% premium above the pasture rental rate to convert pasture to dedicated switchgrass production.[152]
- Remaining baseline acreage, that is, 25% of CRP acreage and failed cropland and 10% of harvested cropland, is available at heterogeneous opportunity costs as proxied by the CRP offers data.
- All biomass suppliers in a CRD receive the same price for biomass.

Figure C.5.1 compares the estimated supply curve from the baseline results to the estimated supply curve when biorefineries face different opportunity costs for pastureland and marginal cropland. With lower pasture rental rates relative to CRP bid rates, 83 out of the 182 CRDs utilize only pastureland for switchgrass production. The least cost ethanol ($3.10 per gallon) is produced at a 114 mgy biorefinery located in northeast Texas which procures switchgrass grown on pastureland only. Relative to the baseline results, the allocation of less land for biomass leads to smaller capacity biorefineries (-7 mgy) and lower cumulative capacity (-1.2 bgy).

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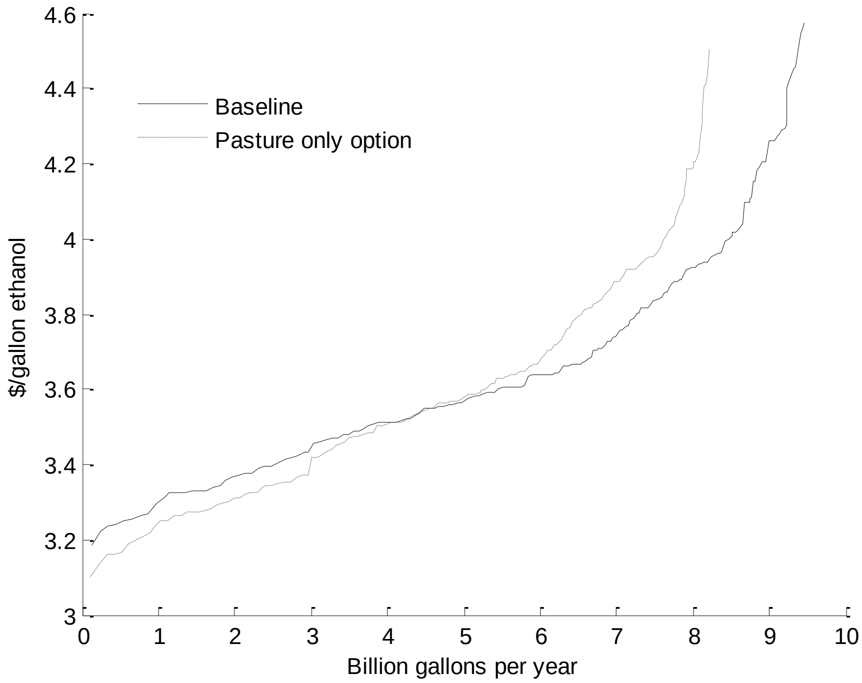
[152] The assumption of a 15% premium follows from de la Torre Ugarte, Walsh, Shapouri, & Slinsky (2003).

Figure C.5.1 – Estimated supply curves from baseline results and pastureland only option



Additional land option

Baseline results follow previous literature by limiting the acreage in each CRD that is allowed to convert into switchgrass production. Here, we relax this constraint. If the biorefinery offers a high enough price for switchgrass, additional (higher opportunity cost) land may be converted to switchgrass production. We make the following assumptions in order to evaluate the potential impact on model results from allowing additional land to convert to switchgrass production:

- Baseline acreage is available at heterogeneous opportunity costs as proxied by the CRP offers data.
- Land beyond the baseline acreage is available but at a higher opportunity cost. Empirical estimates of cropland and pastureland own-price/return elasticities are used to determine the increase in acreage supplied for switchgrass production from an increase in the price of switchgrass.
- Total switchgrass acreage is constrained above by total pastureland, CRP land, cropland pasture, failed cropland, and harvested cropland in each CRD.
- All biomass suppliers in a CRD receive the same price for biomass.

Without data on switchgrass land use, we use empirical estimates of land use own-price/return elasticities (Table C.5.1) to proxy for the own-price elasticity of switchgrass acreage ($\varepsilon_{A_{SG},P_{SG}}$), or the increase in acreage supplied for switchgrass production from an increase in the price of switchgrass. Estimates for the price elasticity of cropland range between 0.011 and 0.5 and pastureland elasticities range between 0.09 and 0.45. The highest elasticity reported in Table C.5.1 is 0.95 estimated by Miller & Plantinga (1999) for corn and soybean acreage. Based on the values estimated in the literature, agricultural land use is relatively price inelastic.

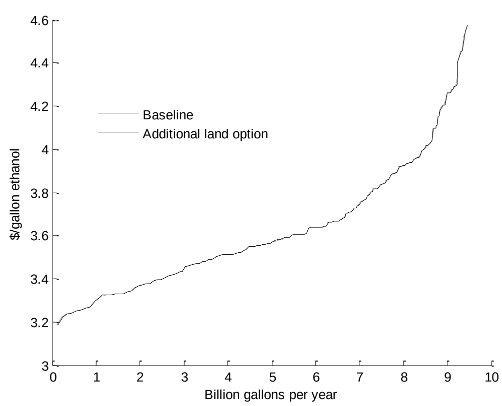
Table C.5.1 – Empirical estimates of land use own-price/return elasticities

Crop/land use	Own price/return elasticity	Source
Corn		
	0.014	Arnade & Kelch (2007)
	0.15	Chavas & Holt (1990)
	0.1	Chembezi & Womack (1992)
	0.05	Lee & Helmberger (1985)
	0.17-0.35	Lin & Dismukes (2007)
	0.95	Miller & Plantinga (1999)
	0.05	Orazem and Miranowski (1994)
	0.2	Tegene, Huffman, & Miranowski (1988)
	0.51	Huang & Khanna (2010)
Cropland		
	0.05-0.41	Ahmed et al. (2008)
	0.5	GTAP (2010)
	0.011-0.192	Lubowski et al. (2006)
	0.09-0.183	Lubowski et al. (2006) – from pasture
Pasture		
	0.26	Gallagher & Shapouri (2008)
	0.23-0.45	Ahmed et al. (2008)
	(N.S.)	Lubowski et al. (2006)
	0.09-0.183	Lubowski et al. (2006) – from cropland
Soybeans		
	0.95	Miller & Plantinga (1999)
	0.45	Chavas & Holt (1990)
	0.25	Lee & Helmberger (1985)
	0.3	Lin & Dismukes (2007)
	0.25	Orazem & Miranowski (1994)
	0.487	Huang & Khanna (2010)
Wheat		
	0.05	Chembezi & Womack (1992)
	0.25-0.34	Lin & Dismukes (2007)
	0.35	Morzuch et al. (1980)
	0.067	Huang & Khanna (2010)

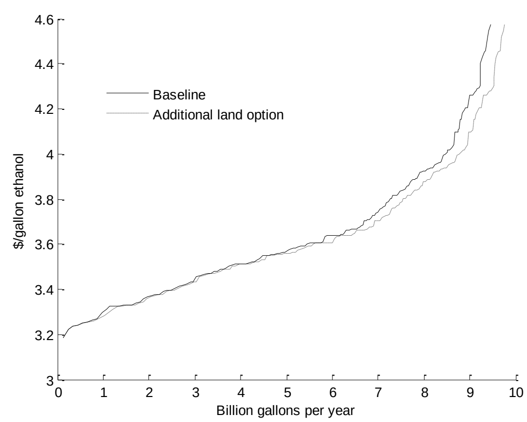
Removing the land use constraint has minimal impact on the estimated supply curve for the range of own-return land use elasticities reported in Table C.5.1 (see Figure C.5.2). In particular, the estimated supply curve is unchanged when the price elasticity of switchgrass acreage is set at the highest pastureland elasticity found within the literature (i.e., $\varepsilon_{A_{SG},P_{SG}} = 0.45$). The cost to incentivize more land to move into switchgrass production outweighs benefits from increased biomass density. Figure C.5.2 shows that the option to convert additional land beyond the baseline acreage into switchgrass only impacts model results for elasticities of switchgrass acreage significantly higher than the values reported in Table C.5.1.

Figure C.5.2 - Estimated supply curves from baseline results and additional land option

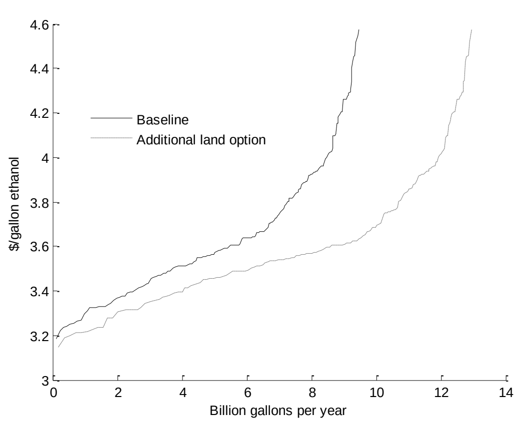
(a). $\varepsilon_{A_{SG},P_{SG}} = 0.45$



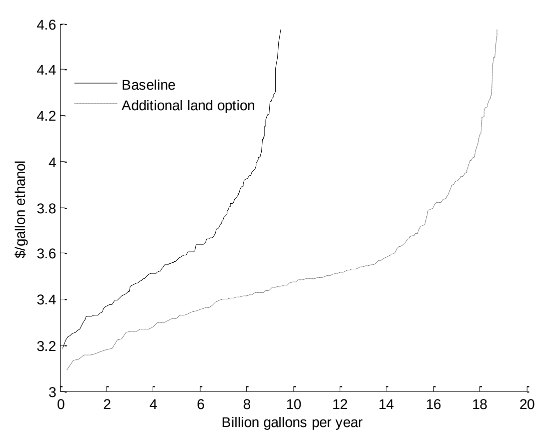
(b). $\varepsilon_{A_{SG},P_{SG}} = 0.95$



(c) $\varepsilon_{A_{SG},P_{SG}} = 2$



(d). $\varepsilon_{A_{SG},P_{SG}} = 4$



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