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TECHNICAL REPORT

Supplying Biomass to Power Plants

A Model of the Costs of Utilizing Agricultural Biomass in Cofired Power Plants

Tom LaTourrette, David S. Ortiz, Eileen Hlavka, Nicholas Burger, Gary Cecchine

Sponsored by the United States Department of Energy

RAND Environment, Energy, and Economic Development

A RAND INFRASTRUCTURE, SAFETY, AND ENVIRONMENT PROGRAM

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Preface

Concerns about greenhouse-gas emissions, escalating and volatile petroleum prices, and the national security implications of U.S. dependence on foreign energy sources have driven efforts to increase the use of renewable energy in the United States. Biomass energy is one potential component of a diversified energy portfolio. In addition to being a renewable resource, generally with lower life-cycle greenhouse-gas emissions than fossil fuels, the biomass resource base is large and diverse. It is also currently the only renewable resource capable of providing liquid fuels. Several national policies enacted in the past decade have stimulated interest in utilizing biomass to generate electricity and to manufacture liquid fuels in the United States. A substantial amount of research has focused on estimating current and future stocks of biomass resources under various future scenarios. Less research has addressed issues surrounding biomass supply at the local scale, such as local land availability, crop choices, cost drivers, and transportation and storage concerns. This report models the processes and costs of utilizing agricultural biomass, specifically switchgrass and corn stover, to generate electricity in cofired power plants. The initial application of the model is for a model plant located in Illinois.

This work was sponsored by the Office of Systems, Analyses, and Planning of the U.S. Department of Energy's National Energy Technology Laboratory (NETL). It is intended to assist NETL in providing guidance to local power-plant operators about introducing biomass into their fuel mix. It should also be useful to potential suppliers of agricultural biomass in understanding issues related to supplying power plants with agricultural biomass. It might also be helpful to local governments in designing effective policies to utilize local agricultural biomass resources to generate electricity.

This report follows two earlier RAND studies for NETL addressing biomass energy resources:

- *Characterization of Biomass Feedstocks*, by David S. Ortiz, Henry H. Willis, Asha Pathak, Preethi Sama, and James T. Bartis, unpublished research, 2008
- *Calculating Uncertainty in Biomass Emissions Model Documentation, CUBE Version 1.0*, by Aimee E. Curtright, Henry H. Willis, David R. Johnson, David S. Ortiz, Nicholas Burger, and Constantine Samaras, 2010.

The RAND Environment, Energy, and Economic Development Program

This research was conducted in the Environment, Energy, and Economic Development Program (EEED) within RAND Infrastructure, Safety, and Environment (ISE). The mission of

RAND Infrastructure, Safety, and Environment is to improve the development, operation, use, and protection of society's essential physical assets and natural resources and to enhance the related social assets of safety and security of individuals in transit and in their workplaces and communities. The EEED research portfolio addresses environmental quality and regulation, energy resources and systems, water resources and systems, climate, natural hazards and disasters, and economic development—both domestically and internationally. EEED research is conducted for government, foundations, and the private sector.

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Contents

Figures

Tables

Summary

Concerns about greenhouse-gas emissions, volatile petroleum prices, and the national security implications of U.S. dependence on foreign energy sources have driven efforts to diversify sources of energy in the United States. Biomass energy is one potential component of a diversified energy portfolio. In addition to being a renewable resource, generally with lower life-cycle greenhouse-gas emissions than fossil fuels, the biomass resource base is large and diverse. It is also currently the only renewable resource capable of providing liquid fuels. Several pieces of national legislation have been enacted to stimulate the development of biomass energy, including the Biomass Research and Development Act of 2000,[1] the Energy Policy Act of 2005,[2] the Energy Independence and Security Act of 2007,[3] and the 2002 and 2008 farm bills.[4] A substantial amount of research on macroscopic, national-scale questions related to biomass resource availability, the environmental implications of biomass energy development, and biomass conversion technologies has been conducted over the past decade. Less research has addressed local-scale questions related to the infrastructure and logistics of supplying biomass and the costs of and constraints on the cultivation, collection, transportation, processing, and storage of biomass. Prospective biomass fuel users, such as power plants and liquid fuel refineries, need this information in order to make considered decisions on the location, size, operation, and other issues involved in making an investment in a facility that utilizes biomass.

The model developed in this work is designed to estimate the cost and availability of biomass energy resources from U.S. agricultural lands from the perspective of an individual power plant. In the example used in this report, the model estimates the availability and cost of using switchgrass or corn stover to power a cofired power plant. For the purposes of explication, we site the plant in this example in Illinois. The model provides information about the plant-gate cost of producing biomass fuel, the relative proportions of switchgrass and corn stover, the mix of different land types, and the total area contributing the supplied energy. Although the findings are sensitive to local details and quantitative results hold only for the corn-belt region, most findings are qualitatively generalizable.

1 Title III of Pub. L. 106-224, 2000.

2 Pub. L. 109-58, 2005.

3 Pub. L. 110-140, 2007.

4 Pub. L. 107-171, 2002; Pub. L. 110-246, 2008.

Modeling Approach

We model the supply of biomass to a single plant at the county level. Each unique combination of county, crop, and land type is treated as a discrete unit of supply. The model includes four crop-land-type combinations (corn stover grown on corn acreage, and switchgrass grown on cropland, cropland pasture, or Conservation Reserve Program [CRP] land). For each supply unit, we estimate the mass of biomass supplied and cost at the power-plant gate. Cost comprises land access costs, crop cultivation and harvesting costs as appropriate, and transportation and storage costs. Then the supply units are ordered by cost, from lowest to highest, to derive a marginal cost curve of supplied biomass.

We also examine the sensitivity of the results when the government levies a charge on greenhouse-gas (GHG) emissions and when the government provides a credit for carbon storage in land. The mass of biomass is estimated from the land area available and the production yield. The results are used to generate mass supply curves for the power plant. For each point on this curve, the model identifies the crops, counties, and land types supplying that biomass and the total land area used. Results are sensitive to several interdependent parameters, such as crop yields, production and handling costs, power-plant location, and tillage practices. The model encompasses the continental United States and utilizes current land rental rates, crop yields, transport costs, and input prices from available sources.

Our biomass supply model assumes that there is no competition for agricultural biomass in the area serving the plant and that producers of biomass contract individually with the power plant. Under these assumptions, we estimate the break-even price for biomass at which each biomass producer would be indifferent between supplying biomass to the power plant and alternative use of their land. If we were to consider multiple power plants, the catchment areas of those plants would overlap, increasing the average transportation distance (and, hence, costs) of supplied biomass. We capture the opportunity costs for land using rental rates, which makes biomass resource prices a function of existing alternative land uses. For corn stover, we assume that it will be produced only on land currently producing corn. By assuming that the costs of inputs are fixed parameters, we focus on the short-term decision problem faced by a single power plant to procure supplies of fuel.

Results

Utilizing the example of a power plant in Illinois, we conduct our analysis for a base-case scenario. We then examine the sensitivity of the results to changes in several parameter values. The base-case conditions for the example are summarized in Table S.1. These conditions are intended to reflect our best understanding of uncertain parameters and plausible decisions regarding the design of a biomass energy supply system.

A supply curve for the base-case scenario is shown in Figure S.1. This figure shows the biomass production cost as a function of dry weight tons.[5] For reference, we assume that 1 dry weight ton of switchgrass or corn stover equals 17 GJ. For sake of comparison, 1 ton of as-

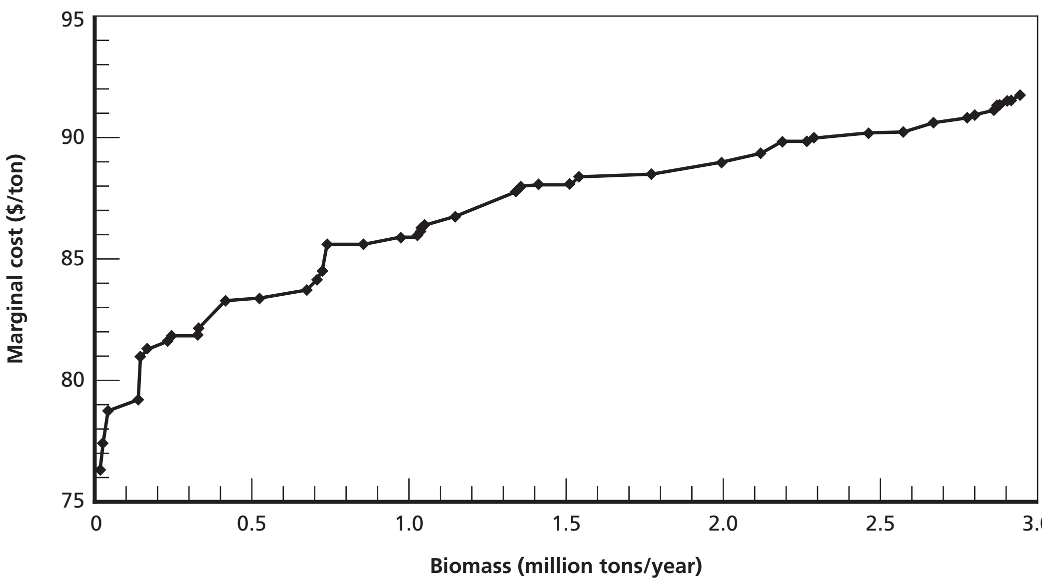
[5] It is common to normalize biomass cost and availability metrics to "dry tons of biomass" due to the variability in moisture content between different biomass types and at different points in the process of bringing biomass to market. Freshly harvested biomass can contain up to 50 percent (by weight) moisture, whereas processed and delivered biomass can contain as little as 5 percent moisture.

Table S.1
Base-Case Scenario Conditions for Illinois Example

Parameter	Value
Power-plant demand	3 million dry tons of biomass per year (approx. 50 million GJ per year)
Power-plant location	Jasper County, southern Illinois
Centralized storage	Included
Production costs	Best estimates
Carbon cost/credit	Excluded
Corn tillage practice	Current tillage mix
Crop yields	Best estimates
Land area available	100% of corn acreage, cropland pasture, and CRP land; 10% of cropland

NOTE: GJ = gigajoule.

Figure S.1
Energy Supply Curve for Base-Case Scenario



RAND *TR876-S.1*

received coal typically burnt in power plants in Illinois contains 18.8 GJ, so 1 dry weight ton of biomass has the energy equivalent of 0.9 tons of coal.[6]

We terminate the supply curve at 3 million tons (51 million GJ per year), which, when burned continuously, would produce 500–600 megawatts (MW) electrical power. As such, it represents the upper limit of the supply of biomass to a single plant. This would be enough to fuel a 30-percent biomass, 70-percent coal cofiring arrangement for the largest coal-fired

[6] This heating value is representative of subbituminous coals from the Western United States. These coals are commonly used in Illinois due to the low sulfur content. Local coals are of the bituminous rank and have heating values up to 25 GJ per ton.

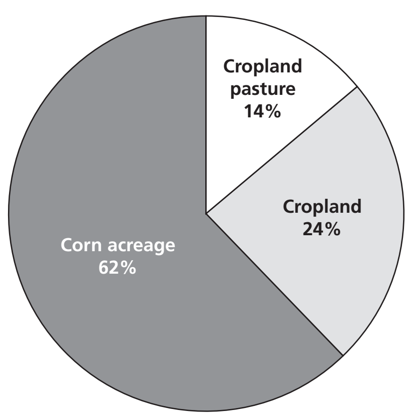
power plants in Illinois (about 1,500 MW). In practice, the amount of biomass supplied would be smaller.

The results show that the production cost ranges between $76 and $91 per dry ton ($4.50 and $5.40 per GJ), which is broadly consistent with other estimates for biomass feedstock prices. In contrast, coal consumed in power plants in Illinois sold at an average price of $1.55 per GJ in 2008–2010. The energy supply for the base-case scenario is drawn from a mix of corn stover and switchgrass from 22 counties surrounding the example power plant, a supply area with a radius of about 70 miles. To produce this amount of biomass, 1.9 million acres is needed. The mix of crops and land types for the base-case scenario for this example is shown in Figure S.2, which shows that 38 percent of the energy comes from switchgrass and 62 percent of the energy comes from corn stover. About two-thirds of the switchgrass energy comes from cropland, and about one-third comes from cropland pasture. The mix of crops and land types is modulated by transportation costs—supply from the sources with lowest land and production costs (generally, switchgrass grown on cropland pasture) is constrained by transportation costs, which increase with distance from the power plant. At higher production levels, more-expensive cropland near the power plant is used to supply biomass, trading increased transportation costs for increased land rent.

The base-case scenario represents our default estimate of the parameter values, but many parameter values are uncertain, either because they fluctuate (e.g., crop yields, input prices) or because their values depend on decisions about the design of a biomass production system (e.g., power-plant location, crop and land type, tillage practices, biomass storage). Consequently, we conducted sensitivity analyses by estimating a number of alternative supply curves, altering various parameter settings. The results of the sensitivity analyses are summarized in Table S.2.

There is substantial uncertainty concerning biomass crop yields. Furthermore, the scientific community does not have a very good sense of the potential for yield growth as seed varieties and management practices improve. Yield estimates for best-case conditions (95th-percentile switchgrass yields or collection quantities associated with no-till corn cultivation) are about 40 percent and 70 percent greater than our base-case assumptions for switchgrass and corn stover, respectively, although these higher estimates probably reflect minimum yield

Figure S.2
Distribution of Land Types for Base-Case Scenario for Illinois Example



RAND *TR876-S.2*

Table S.2
Summary of Sensitivity Analyses

Scenario	Average Cost ($/ton)	Average Cost ($/GJ)	Harvested Area (million acres)	Fraction of Energy from Switchgrass
Base case	87	5.12	1.9	0.37
95th-percentile switchgrass yields	74	4.36	0.36	1.0
No-till corn cultivation	81	4.76	1.5	0.06
Increase stover production cost 50%	93	5.45	0.51	1.0
Increase switchgrass production cost 50%	90	5.29	2.7	0.00
Increase both production costs 50%	110	6.44	1.5	0.51
Power plant in central Illinois	86	5.06	2.4	0.02
Power plant in southernmost Illinois	84	4.94	0.55	0.97
No intermediate storage	70	4.10	2.0	0.34
Corn stover only	90	5.29	2.7	0.00
Switchgrass only	93	5.45	0.51	1.0
Supply from corn acreage only	90	5.29	2.7	0.0
Supply from cropland only	96	5.66	0.49	1.0
Supply from cropland pasture only	105	6.20	0.53	1.0
Supply from CRP land only	104	6.12	0.54	1.0
Carbon cost = $20/metric ton CO_2e	89	5.26	0.49	1.0
Carbon cost = $100/metric ton CO_2e	67	3.97	0.49	1.0

NOTE: CO_2e = carbon dioxide equivalent. The declining average cost of biomass as the cost of carbon increases is due to an assumed credit for carbon sequestered by the switchgrass.

increases over the long term. These yield increases would decrease total supply costs by about 17 percent and 10 percent for switchgrass and corn stover, respectively. There is also considerable uncertainty about the costs of switchgrass production and harvesting and corn-stover collection. Production costs account for about half of the total supply cost, so, if production costs for both crops are higher than expected, total costs increase proportionally by about half as much as the increase in production costs.

Factors that vary with system design include power-plant location, the use of intermediate storage, crop and land-type constraints, and carbon costs. Within central and southern Illinois, the location of the power plant has a relatively small effect (plus or minus approximately 5 percent) on energy cost. However, location has a significant effect on the distribution of the lowest-cost biomass crops, which changes from nearly pure corn stover in central Illinois to nearly pure switchgrass in southern Illinois. Biomass crops are harvested once or twice per year, so biomass fuel must be stored to provide year-round fuel to a power plant. Eliminating intermediate storage would reduce costs by about 20 percent. However, without intermediate storage, biomass would need to be stored on farms or at an energy facility, which would also

entail some costs. Eliminating intermediate storage might only transfer costs elsewhere without reducing total costs.

Because corn-stover and switchgrass costs are similar, restricting production to one crop or the other (e.g., if the cost or access to one changed significantly) has a relatively small effect on total cost (less than 7 percent) because eliminating one crop shifts production to the other crop with relatively little change in total cost. Restricting switchgrass production to a particular land type could have a more-substantial effect on costs. Restricting switchgrass production to cropland pasture or CRP land can increase supply costs by as much as 21 percent, primarily because the area of these lands is limited in the region considered, requiring greater transportation distances. A government-imposed charge on emissions of carbon dioxide and credit for carbon storage can have a large effect on both total supply cost and crop and land-type distribution. As charges and credits increase, supply shifts entirely to switchgrass on cropland. This is due to the reduced life-cycle GHG emissions associated with cultivating switchgrass as compared to corn stover—namely, removal of corn stover has been shown to lead to releases of soil carbon, resulting in a net penalty to corn stover, while switchgrass has been shown to sequester carbon in its root system, resulting in a net benefit.

Implications for the Supply of Biomass

We conclude our analysis by exploring how variations in crop yields and various charges for emissions of GHGs would influence the supply of biomass to a cofired power plant. We analyze the characteristics of supplying biomass to an energy facility in four cases: the base case described above, a case in which switchgrass yields are reduced by 20 percent, a case in which corn-stover collections are reduced 20 percent, and a case in which GHG emissions are priced at $25 per ton of CO_2e.

The cost of delivering biomass does not change significantly under the four cases. The average cost of supplying 3 million dry tons ranges from $86 to $89 per dry ton. The cost does not vary much because corn stover and switchgrass have similar costs and freely substitute for one another. Changes in supply area and land use are more significant. Our analysis reveals three important implications for amount and distribution of crop and land types that supply biomass fuels for energy production.

One, relatively small variations in crop yields can lead to substantial changes in the amount, type, and spatial distribution of land that would produce the lowest-cost biomass for an energy facility. Under reduced switchgrass yields, the lowest-cost biomass energy is supplied almost entirely by corn stover, collected over a wide area of corn acreage. Under decreased corn-stover yields, the biomass supply shifts to predominantly switchgrass. Switchgrass production requires only about one-fifth of the amount of land that corn stover does, but switchgrass production displaces food production on cropland. In addition, the highest-yielding corn acreage is to the north of the chosen plant location, while the highest-yielding switchgrass lands are to the south. This means that the geographic area over which biomass is collected changes considerably as relative yields vary. The large effect of yields on the distribution of supply could make it difficult to predict from year to year what and where the most cost-effective biomass sources will be. Plant operators would have to arrange to procure biomass from a wide range of suppliers in the vicinity of their facility to hedge against potential shifts in production and changes in costs.

Two, land and crop choices would be very sensitive to policies governing GHG emissions and carbon pricing. When a price is placed on emitting GHGs and credit given for storing carbon, the lowest-cost supply rapidly shifts to entirely switchgrass, nearly all of which is planted on converted cropland. This is due to significantly lower GHG emissions of switchgrass. In devising a supply strategy for sourcing biomass energy from agricultural lands, plant operators should be cognizant that production costs are highly sensitive to exogenous factors and that supply areas might change dramatically under relatively modest changes in key parameters.[7]

Three, our results have important implications for total land area requirements for supplying biomass fuel. Replacing one-fourth of the coal used for electricity generation in Illinois (about half of the electricity in Illinois comes from coal) with biomass fuel would require collecting corn stover from almost 12 million acres of corn crops, nearly all of the corn grown in the state. Alternatively, restricting biomass production to switchgrass would reduce the land requirement to 3.2 million acres, almost half of which would be converted food cropland. In this instance, 6 percent of the state's food crop production would be displaced by biomass production for energy. In either case, the land-use implications are substantial; environmental loading, transportation needs, and workforce requirements, among other areas, would be affected significantly.

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[7] Some of these parameters include the value of the soil-carbon penalty that results from collecting corn stover and the GHG allocations among corn coproducts. Additionally, including GHG emissions due to indirect land-use change would have an effect. Qualitatively, the results do not change: The carbon penalty associated with collecting corn stover results in it being uneconomic as a the price on GHG emissions rises.

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Abbreviations

CO_2e	carbon dioxide equivalent
CRP	Conservation Reserve Program
CUBE	Calculating Uncertainty in Biomass Emissions
DOE	U.S. Department of Energy
EEED	Environment, Energy, and Economic Development Program
EIA	Energy Information Administration
FSA	Farm Service Agency
GAO	U.S. Government Accountability Office
GHG	greenhouse gas
GJ	gigajoule
ISE	RAND Infrastructure, Safety, and Environment
Mg	megagram
MW	megawatt
NETL	National Energy Technology Laboratory
NREL	National Renewable Energy Laboratory
Pub. L.	Public Law
USDA	U.S. Department of Agriculture

CHAPTER ONE

Introduction and Motivation

Biomass energy resources consist of plant and animal matter that is used to produce heat, electricity, or liquid fuels. Biomass energy resources are diverse and include municipal wood waste; residues collected from forestry operations and fire thinnings; agricultural residues, such as corn stover and wheat straw; manures; and dedicated energy crops, such as switchgrass (Perlack et al., 2005). Although a substantial amount of liquid biofuel is generated from corn and soybeans, relatively small amounts of biomass—principally, forestry residues, wood residues, and wood wastes—are used to produce heat and power. The federal government has enacted several pieces of legislation to stimulate the development of biomass energy, including the Biomass Research and Development Act of 2000, the Energy Policy Act of 2005, the Energy Independence and Security Act of 2007, and the 2002 and 2008 farm bills (Biomass Research and Development Board, 2008). These policies have raised awareness of the potential of biomass fuels and stimulated increased investigation into the availability of biomass resources and the infrastructure and logistics required to support a full-scale biomass supply industry.

A growing body of literature has examined the feasibility and energy potential of various biomass resources. These studies have laid the groundwork for a number of integrative projections of future biomass resource availability under different policy, land-use, climate-change, technology-development, and economic scenarios. A 2005 study led by Oak Ridge National Laboratory estimated the amount of biomass energy that could be produced annually in the United States under several alternative scenarios of crop yields and land-use changes (Perlack et al., 2005). That study estimated that the U.S. biomass resource from agricultural lands ranges from approximately 190 million dry tons (3.2 billion gigajoules [GJ][1]) today to almost 1 billion tons (17 billion GJ) if yields improve significantly and cropland currently used for food crops is dedicated to producing biomass for energy. Production of 190 million dry tons of biomass could generate about 300 terawatt-hours of electricity, approximately 8 percent of 2008 U.S. consumption (Energy Information Administration [EIA], 2010). For comparison, U.S. coal production in 2008 was approximately 25 billion GJ. Similarly, Milbrandt (2005) estimated that biomass residues—including crop, mill, and forestry residues—could total 320 million metric tons (5.5 billion GJ) and that dedicated energy crops grown on Conservation Reserve

[1] We have used a conversion factor of 17 gigajoules (or GJ, equal to 109 joules) per dry short ton of biomass to estimate the energy content. This is consistent with measured values for switchgrass and corn stover in the National Renewable Energy Laboratory (NREL) Biomass Feedstock Property and Composition Database (Energy Efficiency and Renewable Energy, 2006).

Program (CRP)[2] land could add as much as an additional 84 million tons (1.4 billion GJ). More recently, a National Academy of Sciences panel estimated that agricultural lands can currently produce 220 million tons (3.7 billion GJ) of biomass and could produce up to 320 million tons (5.4 billion GJ) of biomass by 2020 (National Research Council, 2009). Many national estimates incorporate economic considerations, such as biomass fuel prices and competition from alternative land uses, to generate national-level supply curves (e.g., Biomass Research and Development Board, 2008; Walsh, 2008; Kumarappan, Joshi, and MacLean, 2009). A review of biomass supply studies by Gronowska, Joshi, and MacLean (2009) found that projections that did not consider economic constraints ranged from 209 million to 4.2 billion tons (3.6 billion to 72 billion GJ) per year; projections that included economic constraints ranged from 7 million to 635 million tons (119 million to 10.8 billion GJ) per year.

Although these and other studies are useful from the perspective of national resources, they do not provide information needed by potential investors in facilities that use biomass or for potential producers. In contrast to coal or natural gas, which are often sourced from great distances and can generally be treated as commodities, biomass supply is more locally dependent. Compared to fossil fuels, biomass is widely available geographically, lacks an existing supply infrastructure, has a lower energy density, and is more costly. For these reasons, biomass must be supplied locally, and supply characteristics therefore depend strongly on local conditions. Choices about biomass supply for an individual energy facility are influenced by the local availability and cost of potential resources. A substantial part of the cost of supplying biomass is transporting it from the farm to the plant. Decisions about crop and land types used for biomass supply hinge on balancing input from higher-cost lands and crops near the plant with lower-cost lands and crops farther away. Similarly, if a goal of using biomass to produce energy is the reduction of greenhouse gas (GHG) emissions when compared to fossil fuels, decisions related to cultivation practices, crop choice, and land types will affect the potential benefit. A national or regional estimate of biomass resources provides no insight into such trade-offs and so is less helpful for understanding which lands and crops would be used for biomass supply, particularly in the early growth stages of biomass energy production.

In addition, only plant-level analyses provide insights into the total land area and transportation distances required to supply biomass to a particular plant. Information about the collection area is important for understanding the potential evolution of a biomass energy industry. The distribution of current fuel sources and fuel transportation systems for electricity and liquid fuel production (i.e., coal, oil, and gas infrastructure) are very different from those for biomass. Transitioning to biomass fuel sources might influence the optimal distribution or size of energy facilities.

The objective of this report is to characterize the cost, availability, and land-use implications of supplying biomass from U.S. agricultural lands from the perspective of an individual energy facility. To do so, we created a model to estimate plant-gate costs of biomass fuel that takes into account crop yields, the availability of different land types, land costs, GHG reductions, production and collection costs, and transportation and storage costs. The model provides estimates of the cost of supply, the amount supplied at a specified cost, the mixture of residues and farmed energy crops in sourced biomass, the amounts of different types and of

[2] The CRP is a voluntary program administered by the U.S. Department of Agriculture (USDA) Farm Service Agency (FSA) that encourages farmers to withdraw environmentally sensitive land from production (Natural Resources Conservation Service, 2011).

land used to produce the biomass, and the total catchment area (geographic area of the counties supplying biomass) needed to supply the biomass. Estimating amounts and types of land needed to provide biomass makes it possible to evaluate the economic viability, life-cycle GHG emissions, impacts on food crop production and price, and other societal implications of producing biomass energy resources from agricultural lands. Our analysis focuses on supplying a single plant. This situation represents the minimum supply cost. In a situation in which two or more plants seek access to the same supply, costs must rise.

The model uses publicly available, county-level data from USDA and the scientific literature and is designed explicitly to be transparent in its approach and methods. It operates at the county level and covers the continental United States. For the purposes of illustration, we first apply the model to central and southern Illinois. Future analysis might compare the costs, crops, and land-use implications of supplying additional types of biomass across locations. The key required inputs to the model are crop production cost and estimated yields at the county level.

The model includes two biomass crops: switchgrass and corn stover. Switchgrass is a perennial grass that is currently produced in small quantities as a dedicated energy crop. The U.S. Department of Energy (DOE) has identified switchgrass as a "model" energy crop based on its high yields, deep rooting characteristics, potential value in carbon sequestration, tolerance for cool temperatures, and ability to be grown on a variety of land types and climates with conventional farming practices (Wright, 2007; Khanna, Dhungana, and Clifton-Brown, 2008). Corn stover is an agricultural residue. Agricultural residues are by-products of existing agricultural production, so production does not require converting current land use. Although the dominant agricultural residue available for biomass supply is regionally dependent, corn stover is a substantial resource in large parts of the midwestern and eastern United States. Switchgrass and corn stover are both herbaceous biomass feedstocks that have similar processing requirements at the plant site (Sokhansanj and Fenton, 2006).

This analysis focuses on supplying switchgrass and corn stover to cofired coal-fired power plants,[3] although the results are applicable to supplying biomass for cellulosic liquid fuel production as well, as the same feedstocks are used in both applications.

Organization of This Report

Chapter Two describes our cost and energy model, including a summary of the use of switchgrass and corn stover as biomass fuel, the different land types considered in our model, and each of the parameters in our cost model. Chapter Three presents the results of the model for an example in Illinois and investigates the effects of several measurement uncertainties and decision variables on the types of crops grown, location of production, and cost. Chapter Four provides an example of how the model can be used to identify key sourcing issues from the perspective of an energy facility. Appendixes A and B provide further details of the production costs and transportation and storage costs, respectively.

[3] A power plant cofires when it augments its primary fuel with a secondary fuel. For this analysis, we are assuming that biomass augments a fraction of the coal used at a coal-fired power plant.

Modeling Biomass Energy Supply from Agricultural Lands

To help understand the characteristics of supplying biomass fuel to generate electricity for an individual power plant, we developed a model to calculate energy supply as a function of cost. We use this model to calculate supply curves that describe the unit cost of biomass energy as a function of the amount of energy supplied. In addition to cost, the model describes the area required and relative proportions of different crops and land types used to produce the energy. The principal elements of the relationship between energy and cost are the crops considered, their yields, energy densities, land access costs, crop production and collection costs, transportation and storage costs, and potentially the cost of compliance with reducing emissions of GHGs. This chapter describes the modeling approach and discusses the different model inputs.

Cost Model for Supplying Biomass

Supplying biomass from agricultural land for energy production entails three steps: (1) allocating land for biomass production, (2) growing and harvesting the biomass crops, and (3) transporting and storing the harvested crops for use at a power plant. The cost of supplying biomass energy to a power plant is therefore expressed by the general relationship

$$\text{cost of biomass} = \text{land cost} + \text{crop production cost} + \text{transportation cost} + \text{storage cost}. \quad (1)$$

Although different crops can have differing energy densities (energy per mass), the energy densities of switchgrass and corn stover differ from each other by less than 2 percent. We therefore report costs in terms of cost per mass to facilitate comparison with other studies.

The amount of land required to produce a given amount of biomass depends on its productivity, so land costs depend on both the cost per area of the land and the production yield (mass per area) of the biomass crop being produced. That is, land cost is the land value divided by the crop yield. Production costs also vary with crop yields. Crop yield is hence a critical parameter in estimating biomass cost and supply.

In our analysis, we model costs at the county level. We start by selecting a location for the power plant to which the biomass energy is being supplied. A cost is then computed for each combination of crop and type of land in each county in the vicinity of the plant location. Each unique combination of county, crop, and land type is treated as a discrete unit of supply. The mass of biomass produced from each supply unit is calculated from the relationship

$$\text{mass} = \text{area} \times \text{yield}. \quad (2)$$

The individual supply units are then rank-ordered from lowest to highest cost, and a supply curve is constructed by pairing the cumulative mass with the cost per mass at that point. This approach identifies the lowest-cost supply for the power plant up to any demand level desired.

In the following sections, we discuss crops and land types included in our analysis and each of the cost elements. The discussion describes the data used in our analysis, parameter estimates, and the uncertainties regarding parameter values. Because biomass to supply power-plant locations near state borders might be drawn from neighboring states, we include data for counties in Illinois, Indiana, Kentucky, Missouri, and Iowa in our analysis.

Agricultural Crops for Biomass Energy

For purposes of illustration, we apply our model to sites in central and southern Illinois. Given the predominance of agricultural land in central and southern Illinois, non–agriculturally derived biomass energy resources are relatively small. Consequently, resources derived from agricultural lands are expected to account for virtually all the total biomass energy production in this area.

Agricultural lands can produce three principal forms of biomass energy. The most-common form today is food crops used for the production of liquid fuels. In the United States, ethanol from corn grain and biodiesel from soybean oil are the primary examples. Agricultural lands can also produce dedicated biomass energy crops grown explicitly for the purpose of producing biomass energy. Finally, agricultural residues can be recovered and used to produce liquid fuels or burned to produce heat or electric power.

In this study, we consider switchgrass, a dedicated biomass energy crop, and corn stover, an agricultural residue, as potential sources of biomass energy from agricultural lands. Corn production in southern and central Illinois is among the highest in the country, so this is an area in which corn residue could be expected to compete with dedicated biomass energy crops. Focusing on these two biomass energy sources allows us to investigate trade-offs among biomass energy resources, agricultural residues, costs, and the land types used for biomass energy production.

Switchgrass. Switchgrass is a perennial grass, native to the United States (Bransby, undated). Specific strains of switchgrass have been developed to maximize yield as an energy crop. Different strains of switchgrass are better suited to different regions; these strains have been studied and characterized extensively. Mature switchgrass stands have a dense, deep root network that provides drought resistance, prevents soil erosion, and might fix carbon in depleted soils.

Switchgrass crops can be established in three years (McLaughlin, Bouton, et al., 1999). During the first two years of establishment, seedlings are very susceptible to competition from weeds and other pests (McLaughlin and Kszos, 2005). Young plants devote resources to establishing a root system and typically attain one-third to two-thirds of maximum production capacity by the second year (McLaughlin and Kszos, 2005; McLaughlin, Bouton, et al., 1999). During the third year, switchgrass roots become fully established, and plants reach their maximum production capacity (McLaughlin and Kszos, 2005; McLaughlin, Bouton, et al., 1999). The crop production cycle is expected to be ten years, after which a farmer might reseed with a new variety. However, because it is a perennial crop, a switchgrass stand can last indefinitely once established (Graham and Walsh, 1999; McLaughlin and Kszos, 2005; McLaughlin, Bouton, et al., 1999).

Switchgrass can be harvested up to two times per year between years 4 and 10 (McLaughlin and Kszos, 2005). A single annual or biennial harvest requires less energy input and is favored in more-arid regions (McLaughlin and Kszos, 2005; McLaughlin, Bouton, et al., 1999), while a two-cut system with cuts in July and October results in higher yields in the south, which has a longer growing season (McLaughlin, Samson, et al., 1996). Higher yields are consistently obtained if the first harvest occurs in or after July (McLaughlin and Kszos, 2005).

There are several possible ecological side benefits from switchgrass crops. An extensive root mass with rapid turnover below ground permits efficient water and nutrient uptake and addition of organic matter to soils (McLaughlin and Walsh, 1998; Downing et al., 1996). As a result, switchgrass crops exhibit reduced evapotranspiration because of high water-use efficiency and prevent soil erosion and runoff of agrochemicals (McLaughlin and Walsh, 1998). When grown on depleted or marginal lands, switchgrass might be able to build soil carbon (Tilman et al., 2009). Switchgrass can be planted along streams and wetlands to stabilize soils and can prevent sedimentation of wetlands adjoining erosive agricultural fields (McLaughlin and Walsh, 1998). As a perennial crop, switchgrass can grow for many years without a replanting cycle, decreasing soil loss and degradation (McLaughlin and Walsh, 1998).

With respect to wildlife, switchgrass plantings offer habitat, protective cover, and food (Murray et al., 2003; McLaughlin and Walsh, 1998; Downing et al., 1996). The timing of the first cut of a two-cut system might affect certain types of birds in some areas; it has been suggested that appropriately managed single-cut systems have less of an effect on nesting birds (McLaughlin and Walsh, 1998). Roth et al. (2005) suggest that leaving certain fields unharvested can allow switchgrass plantings to support bird species that prefer taller or shorter grass.

Corn Stover. Corn stover is the agricultural residue of the corn plant after harvesting. It consists of the stalks and leaves of the plant; depending on the harvesting method, it can also consist of the cobs and husks (Aden et al., 2002). Corn stover is often left in the field, where it helps to prevent erosion, maintains soil moisture content, and adds some nutrients to the soil (Graham et al., 2007). A portion of the corn stover can be collected from the field and used as a biomass energy input (Wilhelm, Johnson, Karlen, and Lightle, 2007). Corn stover can also be used in silage.

Corn is typically planted in early April, though planting can occur several weeks later in northern regions. Time to harvest can vary with different hybrids. Crops are usually harvested in September and October, but harvests may be delayed in cooler years or to allow kernels to dry in the field for longer, thus permitting longer storage times.

The removal of corn stover from fields can have significant but as yet inadequately quantified environmental consequences; further research is required to determine more precisely the amount that can be collected sustainably. When left in the field, corn stover helps soil to retain organic matter, which in turn affects soil aggregation and infiltration of water, soil water-holding capacity and evaporation, aeration, pH, nutrient availability and cycling, ion exchange capacity, and buffering capacity (Wilhelm, Johnson, Hatfield, et al., 2004). The residue also protects soil against the impact of rain, wind shear, and excessive temperatures (Wilhelm, Johnson, Hatfield, et al., 2004). Corn harvesting and stover collection can compact soil. Additionally, removal of corn stover from the field might incur a loss of soil organic carbon (Anderson-Teixeira et al., 2009).

Agricultural Lands Available for Producing Biomass Energy

Agricultural land in the United States is classified as cropland, woodland, permanent pasture and rangeland, land in CRP and other conservation programs, or land in farmsteads, buildings, livestock facilities, ponds, roads, or wasteland (USDA, 2009). Cropland is land that is used to produce crops for harvest. It is primarily used to grow commodity crops (corn, soybeans, cotton, and wheat), other food crops, or hay, but might also lie fallow or be used for pasture (USDA, 2009). Our analysis considers four land types and uses:

- cropland used for growing corn (corn acreage)
- other harvested cropland (cropland)
- cropland used as pasture (cropland pasture)
- CRP land.

CRP is a voluntary program administered by the USDA FSA that encourages farmers to withdraw environmentally sensitive land from production (Natural Resources Conservation Service, 2011). Although both cropland and permanent pastureland are eligible for CRP, virtually all CRP land is retired cropland (FSA, 2009a). Farmers enter into a contract, typically lasting ten years, to withdraw land from production and cultivate a conservation cover crop. The intent of CRP is to reduce soil erosion, to protect groundwater supplies, to limit sedimentation in streams and rivers, and to provide habitat. USDA provides farmers a payment tied to the rental rate that the land would yield if used for crop production. Certain energy crops, including switchgrass, have dense root systems that help to build soil carbon content and can be managed to provide conservation benefits while also producing biomass energy (Templeton, 2006).

In our analysis, corn acreage is available for corn-stover production, while switchgrass can be grown on cropland, cropland pasture, and CRP land. Very little commercial switchgrass production occurs today, so it is difficult to predict which land types would be made available for switchgrass production if a biomass energy market were to emerge. Most current switchgrass production is on cropland. However, given the low environmental impact and ecological benefits of switchgrass, CRP has modified contracts to allow commercial switchgrass production on CRP land (e.g., Templeton, 2006; Stickle, 2009). Allowing switchgrass production on cropland, cropland pasture, and CRP land is consistent with recent national projections of biomass resource production (Perlack et al., 2005; Biomass Research and Development Board, 2008).

Switchgrass grown on cropland will displace other crop production, resulting in competition among energy and food crops. As the biomass energy market grows, competition for cropland will increase, driving cropland value and food prices upward. An equilibrium distribution of energy and food crop production on cropland would be determined by the supply and demand characteristics of energy and food crops. Some national biomass resource assessments model this competition and estimate the amount of energy crop production on cropland that would occur under economic equilibrium (e.g., Torre Ugarte et al., 2003; Biomass Research and Development Board, 2008). Drawing on these analyses, we limit the amount of cropland that can be converted to switchgrass production to 10 percent of noncorn cropland. This value is generally consistent with calculations that account for competition between crops.

In a nascent biomass energy market in which only a small number of power plants are utilizing biomass fuel, displacement of food crops would occur only near these power plants. Consequently, the economic effect of displacing food crops would be minimal, and a greater

fraction of cropland near these power plants might be available for energy crop production. We examined the conditions of an emerging market by allowing 100 percent of noncorn cropland to be available for switchgrass production. As expected, the catchment area decreases significantly (about half as many counties are required to supply the same amount of biomass). However, the effect on cost is small: Making all cropland available for switchgrass production decreases the average supply cost by less than 4 percent.

Land Value

When producing biomass energy displaces some other land use, the forgone profit from the displaced land use must be counted as part of the cost of producing biomass energy resources. Producing switchgrass displaces some other use of the land—food crops on cropland, grazing on cropland pasture, or the conservation value of CRP land. The forgone profit from these activities is approximated by the land rental rates. Therefore, we model land values with the land rent values compiled by USDA. The relative value of agricultural land is a function of the soil depth and nutrient quality, local climate, feasibility of irrigation, and other factors. As part of the U.S. Census of Agriculture, USDA collects information on cropland and pastureland rental rates (National Agricultural Statistics Service, undated). Only 2 percent of the cropland in Illinois is irrigated (National Agricultural Statistics Service, undated), so we use the rental rates for nonirrigated cropland. CRP land rents are compiled separately by USDA's FSA (FSA, 2009b). Rent data are compiled at the county level. All rental values used in our analysis are for 2008. Rents are generally greatest for cropland, followed by CRP land (80–90 percent of cropland rent), and least for pastureland (approximately 25 percent of cropland rent). Although there is substantial variability among individual counties, this general ordering reflects the average relative productivity of the different land types: CRP land is typically retired marginal-quality cropland; pastureland cannot be used for most food crop production.

In contrast to switchgrass, corn-stover production does not displace the preexisting land use. Collecting corn stover has a relatively minor impact on corn production. When not collected, corn stover is left on the field and reincorporated into the soil in the subsequent planting cycle. Collecting corn stover therefore increases the depletion of soil nutrients, which necessitates the addition of extra nutrients. We treat this nutrient replacement as part of the production cost; we set the land cost for corn stover to zero.

Production Cost

Switchgrass production entails initial establishment and annual harvesting (Khanna, Dhungana, and Clifton-Brown, 2008; Duffy, 2008; Perrin et al., 2008). Although mature switchgrass is very robust, establishing switchgrass requires intensive agricultural management (see above), which results in an establishment cost premium in the first two to three years. As noted above, switchgrass stands last more than ten years; there are few data concerning constraints on the lifetime of a switchgrass stand. Given the rapid advances in cultivar development (a plant variety developed by selective breeding), genetic engineering, and management practices, however, cost estimates generally assume that farmers would periodically replace existing stands with new crops to take advantage of improved yields or efficiencies (e.g., Perrin et al., 2008). Switchgrass is typically harvested annually by mowing and baling. Using data from Khanna, Dhungana, and Clifton-Brown (2008), we model production cost per acre in terms of an initial establishment cost amortized over ten years and an annual harvesting cost. Details of our production cost calculations are provided in Appendix A. Results from other

studies (Duffy, 2008; Perrin et al., 2008) agree with cost estimates by Khanna, Dhungana, and Clifton-Brown to within about 10 percent.

Corn stover can be collected using a corn combine with the spreader or chopper turned off, which creates a windrow of stover that can be picked up by conventional hay-baling equipment (Perlack and Turhollow, 2003). Combined systems are available that harvest and separate grain from stover in one step. Large round and large rectangular systems bale stover in the field (Graham et al., 2007). Corn-stover collection costs in our model depend on yield and were taken directly from Graham et al. (2007). Costs include collection and baling costs plus replacement of nutrients removed with the stover (see Appendix A).

Crop Yields

Crop yields influence both production costs and energy production. Because they vary depending on the weather, management practices, and crop and cultivar variety, they present growers and purchasers with a substantial degree of uncertainty.

Switchgrass. Switchgrass yields depend on many natural and management factors, such as soil conditions, temperature, precipitation, cultivar type, harvest system, and harvest timing. If harvested in the spring, switchgrass mineral concentration, moisture content, and mass yield are all lower (Adler et al., 2006). The lower yield might be due to the fact that current harvesting and baling systems are designed for summer harvests; advances in technology might improve spring yields (Adler et al., 2006). If harvested in the summer or fall, mineral concentration, moisture content, and mass yield are all higher (Adler et al., 2006). After frost, switchgrass retranslocates nutrients below ground (McLaughlin, Samson, et al., 1996; Adler et al., 2006). A postfrost harvest reduces yields by approximately 20 percent, but improved yields are usually seen in the following year (McLaughlin, Samson, et al., 1996). Seedlings are very sensitive to soil temperature and rainfall; areas with high evaporation rates will likely have alkaline surface soils in which seedlings cannot develop (McLaughlin and Kszos, 2005). Established switchgrass stands have massive root systems that collect water and nutrients in sufficient quantities to maintain stable yields in dry weather. Because of this root system, switchgrass stands have responded after extreme droughts when growing conditions again became favorable (McLaughlin and Kszos, 2005). Extremely wet or dry conditions might result in lower yields (Graham and Walsh, 1999). Switchgrass is tolerant of periodic flooding and can withstand continuous immersion for 30 to 60 days (Graham and Walsh, 1999; Gamble and Rhodes, 1964). Continued research on switchgrass genetics, breeding, and the development of resilient cultivars might result in substantial increases in harvest yields (Downing et al., 1996); for example, while current yields are generally in the range of 4–5 tons per acre-year nationwide (Gunderson et al., 2008), McLaughlin and Kszos (2005) estimate that average yields of 8 tons per acre-year are possible.

Our model uses county-level estimates of switchgrass yields from Gunderson et al. (2008). These authors collected switchgrass yield data from field trials around the country and examined their dependence on such factors as stand age, ecotype, cultivar, precipitation and temperature in the year of harvest, site latitude, and fertilization regime. Although they found that yield depends, to some extent, on all these factors, they were able to adequately model yields solely in terms of ecotype (highland or lowland), precipitation, and temperature. They then predicted county-level switchgrass yields based on 30-year mean climate records. Typical yields for Illinois are about 9 tons per acre per year.

The model yields estimated by Gunderson et al. (2008) are based on the 95th percentile of the observed yield values. They are intended to reflect optimum growing and weather conditions and neglect other yield-limiting factors. For our analysis, we were interested in actual yields and so adjusted the modeled yield values from Gunderson et al. (2008) to approximate the actual observed values in their data set. Gunderson et al. (2008) predict yields for a subset of production data not used in their parameterization and find that the predicted values are about 40 percent greater than observed yields (Gunderson et al., 2008, Fig. 21). We therefore scale the modeled switchgrass yields by 0.7 to approximate current observed values for switchgrass yield. In Illinois, these yields range from about 5 to 8 tons per acre per year.

Corn Stover. The mass of corn stover produced is estimated from the mass of corn grain produced and the harvest index, which is the dry weight ratio of corn grain to total corn plant mass. Following Graham et al. (2007), we assume a harvest index of 0.5, such that the mass of stover equals the dry mass of corn grain (47.3 pounds per bushel).[1] County-level corn grain yields were taken from the USDA Census of Agriculture (National Agricultural Statistics Service, undated). The average yield of corn in Illinois in 2008 was 179 bushels per acre (USDA, undated), or 3.8 dry tons per acre. The average amount of corn stover produced in 2008 therefore was approximately 3.8 tons per acre.

Several factors, primarily environmental, limit the amount of corn stover that can be collected for bioenergy purposes. Excessive removal of corn stover depletes soil organic content and can facilitate erosion, which ultimately reduces land productivity. Corn stover might also need to remain on fields to preserve soil moisture, though irrigation can increase the fraction of collectible corn stover (Graham et al., 2007). Tillage practices also affect the amount of collectible stover. Replacing conventional tillage practices with mulch till or no-till practices decreases erosion and soil moisture loss and therefore can increase amounts of collectible stover. Lastly, equipment currently available for collection can gather no more than 75 percent of the stover in a field (Graham et al., 2007; Montross et al., 2003).

There is considerable uncertainty about the amount of residue that should remain to maintain soil and water quality. The U.S. Government Accountability Office (GAO) notes that it might take several years for current research efforts to compile sufficient data to reduce this uncertainty (Mittal, 2009). A recent review and research editorial concluded that the association of removal amounts and erosion has not been studied carefully enough across different landscapes (Cruse and Herndl, 2009). There is also considerable uncertainty regarding the effect that removing corn stover could have on the retention and potential emissions of soil carbon regardless of tillage practice. In normal corn production, corn stover is left on the field and plowed under in the subsequent planting cycle. Collecting corn stover for fuel therefore results in a net removal of soil carbon. Little is known about how soil carbon losses constrain stover removal. A recent study by Anderson-Teixeira et al. (2009) indicates that removal of more than 25 percent of available stover results in consistent losses of soil organic carbon ranging from 1.3 to 3.6 tons per acre per year.

In light of the limited understanding of the relationship between stover removal and environmental concerns, the fraction of stover that might be collected for biomass energy is

[1] The harvest index for corn has been increasing in recent years. Johnson, Allmaras, and Reicosky (2006) estimate a mean harvest index of 0.53, which would lead to stover yields about 10 percent lower than those we estimate using a harvest index of 0.5. At the same, corn crop yields have also been increasing steadily over time (USDA, 2011), which would have the opposite effect of increasing stover yields.

uncertain. We estimate stover collection yields from the work of Graham et al. (2007). They use tolerable soil loss values and soil moisture constraints to estimate the amount of stover that should remain in fields to prevent water and wind erosion. Graham et al. find that the amount of collectible stover varies considerably among states, ranging from zero to about 60 percent for current tillage practices. They also estimate that using no-till cultivation would increase the amount of collectible stover by 73 percent. In Illinois, for example, 34 percent of stover can be removed with current tillage, which results in stover removals of 0.7 to 1.6 tons per acre.

Transportation and Storage Cost

Our estimate for transporting and storing baled switchgrass and corn stover is based on custom rates for agricultural services and recent experience with storing switchgrass. For transportation, bales with a given mass and volume are transported on flatbed trailers. Costs per mass per distance (i.e., dollars per ton-mile) are calculated from trailer capacity and contract trucking rates.

An important cost element in our model is intermediate storage of baled switchgrass or corn stover. These crops are harvested once or, in the case of switchgrass, perhaps twice, per year and so must be stored in order to supply a steady year-round stream of fuel to a power plant. In principle, this storage could occur at the farm, at the power plant, or at an intermediate facility. Experts with whom we spoke emphasized that power plants could store small amounts of biomass fuel (i.e., a few days' worth) but generally had neither the space nor the interest to store large stockpiles. Storage at the farm might be feasible, as an individual farm would require far less storage capacity than a power plant storing biomass from dozens of farms. Switchgrass harvested in support of a DOE test at Chariton Valley, Iowa, was stored in purpose-built covered barns with a capacity of several thousand bales (Antares Group, 2009; Miles, 2009).

Storage might affect biomass properties. Storing switchgrass for several months allows silica in the switchgrass to dissipate, reducing potential issues if burned or gasified (Leesley, 2009). Baled biomass might degrade biologically during storage. The extent of loss of biomass from degradation during storage of switchgrass varies depending on storage type. Research on storage methods has provided some data on loss rates (McLaughlin, Samson, et al., 1996). Outside storage of bales on a crushed-rock substrate for 8.5 months might incur losses of 2 to 4 percent. Storage of switchgrass as twine-wrapped bales on sod for 8.5 months might incur losses of up to 15 percent. When initial bale moisture and wrapping are variable (13 to 22 percent moisture for net or twine wrapping, respectively), storage for 12 months might incur losses between 5 and 11 percent. No data are available for losses from indoor storage, but experts with whom we spoke indicated that losses were minimal (Leesley, 2009; Miles, 2009). As indoor storage is assumed, we neglect any potential storage losses in our analysis.

As with many aspects of predicting how a biomass supply system might emerge, it is unclear how biomass will be stored. In our analysis, we assume that biomass will be stored in dedicated intermediate storage facilities similar to those used in Chariton Valley. Costs include renting the land for storage, construction of storage facilities, and the labor and equipment costs of unloading and reloading bales. Details about our transportation and storage cost calculations are provided in Appendix B.

Life-Cycle Emissions of Greenhouse Gases

We also examined the potential cost implications for biomass production if the federal government should impose a charge on GHG emissions or provide a credit for storing carbon in the soil. The approach of Curtright et al. (2010) was applied to estimate net GHG emissions from biomass production, including vehicle emissions, fertilizer production and denitrification into nitrous oxide, and soil carbon retention or depletion as a function of crop and land type.

The life-cycle GHG emissions depend on the time period considered because changes in soil carbon are greatest immediately after land-use change and decrease with time. The Calculating Uncertainty in Biomass Emissions (CUBE) model (Curtright et al., 2010) allows the user to select different time periods over which to estimate life-cycle GHG emissions: In this analysis, we choose years 2–10, meaning that the emissions due to land clearing are not included but that the soil carbon flux that occurs after land conversion is. Life-cycle emissions for corn stover also depend on how emissions are allocated between stover and corn grain. Because corn would be grown whether or not the stover is collected, the model ignores emissions from planting and harvesting corn and counts only the emissions from stover removal, fertilization beyond what would occur if stover were not collected, and transportation. No-till corn cultivation affects life-cycle emissions by changing the amount of stover that might be removed sustainably, but it otherwise has no effect on the carbon balance (Curtright et al., 2010). Finally, the model does not account for indirect land-use changes, such as forest clearing in other countries to replace crop production displaced by biomass production (e.g., see Searchinger et al., 2008). Because the Curtright et al. model was developed for a fixed amount of corn-stover collection (25 percent), we modified it to allow for variation in the fraction of corn stover collected. Using results from Anderson-Teixeira et al. (2009), we increased carbon soil depletion for corn-stover removal by 0.087 metric tons carbon per hectare per percentage stover removal above 25 percent.

Energy Density

Different energy resources have different energy densities (energy per mass), so masses must be converted to energies to compare energy costs of different fuels (e.g., coal and biomass). Energy densities of corn stover and switchgrass are 16.7 and 17 GJ/ton, respectively (Energy Efficiency and Renewable Energy, 2006).

Land Area

Areas of each land type in each county are used to calculate the biomass energy available in each supply unit. County-level land areas for corn acreage, cropland, and cropland pasture were taken from the USDA Census of Agriculture (National Agricultural Statistics Service, undated). We assume that only cropland not used for corn is available for switchgrass production and that the cropland available for switchgrass is equal to one-tenth of all cropland, excluding corn acreage. This assumption reflects the fact that switchgrass must compete with other crops, and we assume that only 10 percent of noncorn cropland is available for switchgrass production (see discussion of available land areas, above). County-level land area enrolled in CRP is provided by FSA (2009b).

Economic Assumptions in Our Biomass Supply Model

We assume a single biomass facility that purchases biomass from a number of farmers representative of the county. The facility pays each representative farmer a price that covers production costs and the opportunity costs of the land (i.e., land rental rate) through individual contracts. The facility is assumed to be able to practice price discrimination; all surpluses accrue to the bioenergy facility.[2] We chose this approach because it allows our model to calculate the total production costs associated with sourcing biomass energy resources.

Although we capture opportunity costs for land using rental rates—which make biomass resource prices a function of alternative land uses—we do not assume a reservation price for biomass resources. Although there are some alternative uses for switchgrass and corn stover, there is no substantial demand for either product outside of biomass for energy.

Our model also assumes that demand for biomass resources does not affect land rental rates, transport costs, or input prices. These assumptions are reasonable as long as biomass producers act as price-takers and the scale of biomass collection activities is not substantially different from other agricultural activities in the region. Our model calculates prices based on available technologies; specialized technology for producing, harvesting, and transporting biomass resources could reduce production costs and prices.

Questions of Sustainability of Large-Scale Biomass Energy Production

As energy biofuel production has not yet scaled up to a large commercial activity, there remains significant uncertainty concerning many of the environmental factors pertaining to biomass usage. Sufficient energy biomass crops can be produced sustainably in the long term only if soil and water resources are not degraded (see Cruse and Herndl, 2009), if they can be shown not to have a net contribution to GHG emissions greater than other alternatives, and if land-use changes required to sustain them are acceptable economically and culturally.

Balancing these issues is made more complex by the interrelated nature of the factors to be considered. For example, the amount of crop residue left in a field directly affects yield for that harvest but affects future yields as well because residue removal might reduce soil organic matter and nutrient cycling and water retention and adds to the soil. Similarly, the decision of how much crop residue to harvest also affects irrigation and fertilization practices. Irrigation can increase the fraction of corn stover that can be removed while still preserving soil moisture (Graham et al., 2007), but irrigation increases costs, might require water intended for other uses, and can increase soil erosion, runoff, leaching, and volatilization. Removing residue generally increases fertilization requirements and, as a result, increases input costs and life-cycle GHG emissions.

The practice of leasing land to produce energy biomass might be inconsistent with the promotion of appropriate stewardship practices (Cruse and Herndl, 2009), particularly regarding decisions about balancing yield with the amount of residue cover that should remain on harvested land to sustain soil and water quality. Similarly, the demand for consistent biomass

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[2] An alternative approach, which could be implemented in our model, would be to assume that the monopsonist cannot price-discriminate and instead pays a single price—determined by the marginal unit supplied—for every ton per GJ of biomass it purchases. In our model, the only effect this alternative assumption would have would be to raise the total cost of sourcing biomass, because the quantity required by the facility is exogenously determined.

energy production could affect other land-management decisions, such as forgoing standard crop-rotation practices, which could result in nutrient depletion and require higher fertilizer and pesticide inputs (GAO, 2009).

Ecological or cultural issues might need to be considered in selecting a location for energy biomass production, such as the loss—or creation—of wildlife habitat, the change of land use from food to energy biomass production, or the conversion of land considered culturally valuable.

As discussed above, there can be ecological benefits from the production of switchgrass: more-efficient water and nutrient cycling and the addition of organic matter to soils (McLaughlin and Walsh, 1998); soil stabilization and sedimentation of riparian and wetland areas (McLaughlin and Walsh, 1998); and habitat, cover, and food for wildlife, particularly for birds (McLaughlin and Walsh, 1998; Murray et al., 2003). On the other hand, conversion of land from prior uses to biomass energy production can alter the local ecology; although new bird habitats could be created, for example, these might replace naturally existing communities.

Given the uncertainty surrounding the environmental impacts of producing crops for energy generation, it is difficult to forecast which lands might be made available for commercial biomass production. Further research and commercial demonstration efforts will help constrain the acceptable land uses for energy crops. Although some environmentally sensitive lands are likely to be deemed unacceptable, the criteria that will be used to make such determinations have yet to be developed.

CHAPTER THREE

Biomass Supply Costs and Distributions of Land and Crops

We present the results of our model simulations in terms of five key parameters:

- the amount of energy produced
- the relative contributions of switchgrass and corn stover
- the relative contributions of different land types
- total harvested area
- cost.

We present the results in the context of a base-case scenario and then conduct several excursions to examine how results depend on different assumptions. This approach allows us to identify those parameters to which the results are most sensitive and hence of greatest importance in understanding the growth of biomass production capacity.

Base-Case Conditions

Our base-case scenario for the example from southern and central Illinois uses our best estimates for parameter values under current conditions (Table 3.1). We located the power plant used in this example in Jasper County, Illinois, which corresponds to the location of the Newton Power Station, a large (1.1 gigawatt) coal-fired power plant in southern Illinois. Although the location of the power plant designated in the base case is somewhat arbitrary, cofiring biomass with coal at a large existing power plant seems a reasonable starting point. We assume that biomass is harvested annually and that it is stored in an indoor intermediate storage facility to provide a steady fuel stream to the power plant.

We do not include the implications of a charge for GHG emissions or credits for carbon storage in our base-case scenario. We introduce charges in alternative scenarios. The tillage practice used in growing corn affects how much corn stover must be retained in the field and hence how much corn stover might be collected sustainably. Because stover collection cost depends on stover yield, tillage also influences cost. Our base case uses the current mix of tillage practices, taken from Graham et al. (2007).

Our model includes several scaling factors to adjust yields and available land areas. The base case uses corn-stover removal rates equal to those determined by Graham et al. (2007) and switchgrass yields equal to 70 percent of those reported in Gunderson et al. (2008) to approximate the current observed values in their data set (see discussion of switchgrass yield data in Chapter Two).

Table 3.1
Base-Case Parameter Values

Parameter	Value
Power-plant location	Jasper County
Centralized storage	Yes
GHG charges	$0
Tillage practice	Current
Corn-stover removal scaling factor	1.0
Switchgrass yield scaling factor	0.7
Cropland yield scaling factor	1.0
Cropland pasture yield scaling factor	0.9
CRP land yield scaling factor	0.9
Usable percentage of cropland for switchgrass production	0.1
Usable percentage of other lands for switchgrass production	1.0

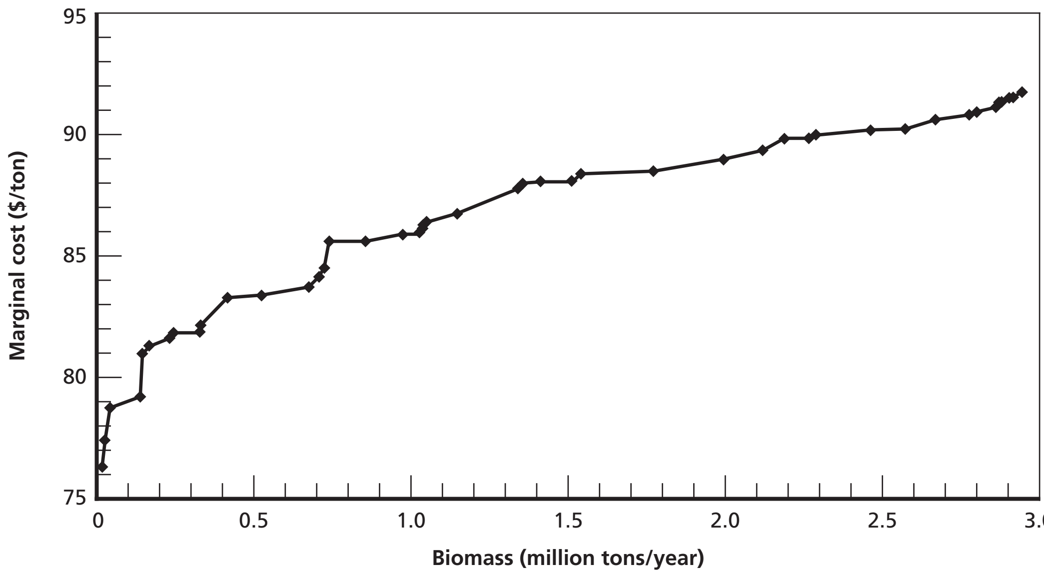
Our model also allows us to vary yields according to the type of land. We were unable to find any data on the relative yields of switchgrass on cropland pasture or CRP land compared to cropland. One study (Downing and Graham, 1996) estimated that switchgrass yields on former cropland pasture were 10 percent lower than on cropland. We use this estimate for both cropland pasture and CRP land.

Because corn-stover collection does not displace corn production, we allow stover to be harvested from 100 percent of the corn acreage. We allow switchgrass to be grown on 100 percent of cropland pasture and CRP land. Since these lands have several uses, some of which would be displaced by switchgrass production, actual availability might be less than 100 percent. Finally, we make 10 percent of noncorn cropland available for switchgrass production. Our model does not account for competition between switchgrass and other crops, so we cannot calculate the equilibrium land balance between switchgrass and other crops. Limiting the cropland available for energy crops to 10 percent is generally consistent with calculations that do account for competition between crops (e.g., De la Torre Ugarte et al., 2003; Biomass Research and Development Board, 2008). Limiting the available cropland area to 5 percent has a minimal effect on the results.

Base-Case Results

Results for the base-case scenario are shown in Figures 3.1–3.5. Figure 3.1 shows the marginal production cost as a function of the mass of biomass produced annually. The cost at any point on the curve is the cost for that increment of energy production; the average cost to produce all the energy up to a given point on the curve will be less than the cost at that point. For example, 1 million dry tons per year could be produced at a cost of less than or equal to $86 per dry ton. Results are presented for production of up to 3 million dry tons per year, which,

Figure 3.1
Supply Curve for Base-Case Scenario



NOTE: For reference, 3 million dry tons of switchgrass or corn stover equals about 50 million GJ, and $90 per dry ton equals about $5.30 per GJ.
RAND *TR876-3.1*

when burned continuously, would produce 500–600 MW electrical power.[1] This would be enough to fuel a 30-percent biomass, 70-percent coal cofiring arrangement for the largest coal-fired power plants in Illinois (about 1,500 MW). Alternatively, this amount of biomass could replace all the coal in a typical coal-fired power plant in Illinois (average capacity = 655 MW; see EIA, 2010b).

Production costs range between $76 and $92 per dry ton ($4.50–$5.40 per GJ). After accounting for the fact that our costs include transportation and storage costs, this range is broadly consistent with other estimates for biomass feedstock prices (e.g., Biomass Research and Development Board, 2008). The delivered price of coal for electricity generation in Illinois from 2008–2010 has been about $1.55 per GJ (EIA, 2010b), which is less than one-third the cost of biomass. As noted in prior studies, this large cost difference means that power-plant operators are unlikely to purchase biomass without a policy intervention, such as a tax on GHG emissions or a mandate insisting on the use of renewable energy (e.g., Khanna, Dhungana, and Clifton-Brown, 2008).

The spatial distribution of biomass costs by the counties that provide biomass under this scenario is shown in Figure 3.2. The location of the power plant, Jasper County, is outlined in white. Figure 3.2 shows that 22 counties, comprising a catchment area with a radius of about 70 miles, are needed to produce the 3 million tons in this scenario. 1.9 million acres would be needed to grow this amount of biomass. The cost for each county is the weighted average of the costs for the four crop–land type combinations possible in each county (corn stover on corn

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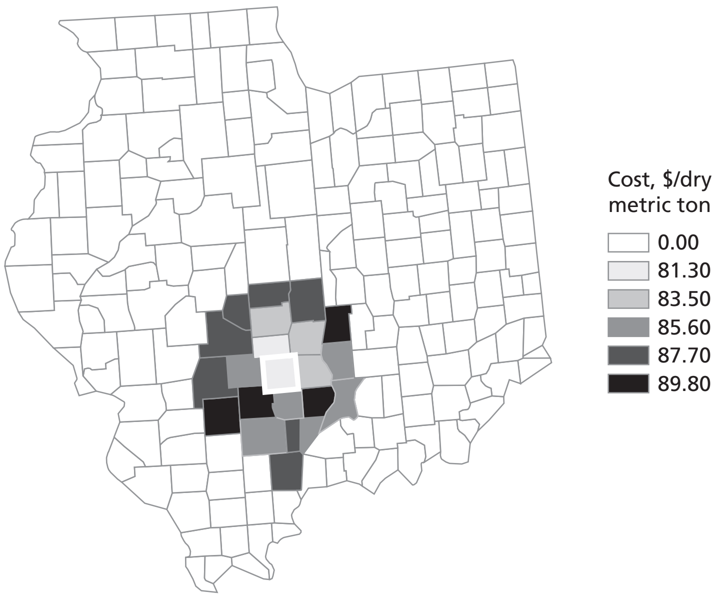
[1] Three million dry tons of switchgrass or corn stover equals 51 million GJ (Energy Efficiency and Renewable Energy, 2006). Burning 51 million GJ in a power plant operating 24 hours per day, 7 days per week over the course of one year is equal to about 1,600 MW thermal, which equates to about 500–600 MW electrical for typical power-plant conversion efficiencies.

Figure 3.2
Distribution of Biomass Cost, by County, for Base-Case Scenario



RAND *TR876-3.2*

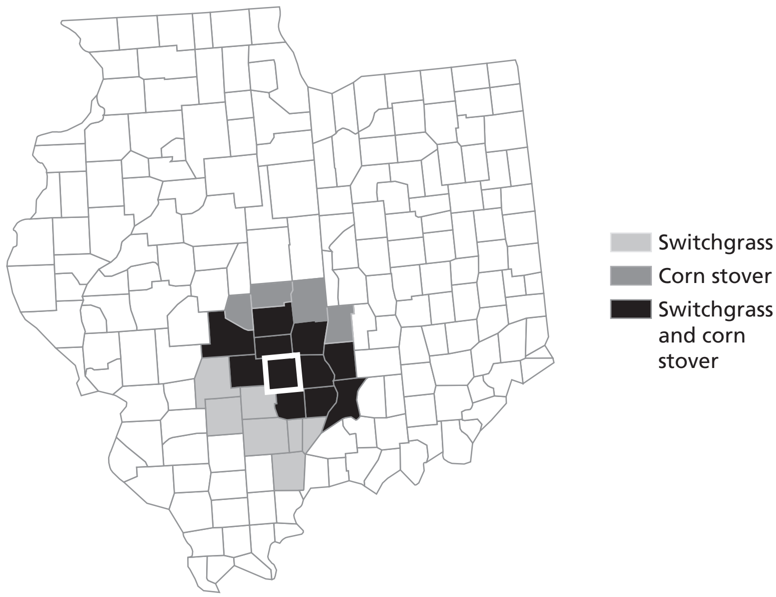
acreage and switchgrass on each of cropland pasture, CRP land, and cropland). Transportation is an important cost element, so costs tend to increase radially away from the power plant. Variations in land cost and crop yield also influence costs, which complicate the distribution. Namely, as more-costly and distant biomass is sourced, it sometimes becomes more economic to convert more-expensive cropland to switchgrass production, trading off increased land costs for reduced transportation costs. Since land near the power plant is limited, marginal supplies tend to come from more-distant lands.

The distribution of the contributions of corn stover and switchgrass is shown in Figure 3.3. This figure shows that the distribution grades from corn stover in the northern part of the production area to switchgrass in the south. This nonuniform distribution results from opposing gradients in the corn stover and switchgrass yield profiles with latitude. Corn grain and stover yields drop from north to south, while switchgrass yields increase. Because production costs are sensitive to yields, the lowest-cost crop transitions from corn stover in the north to switchgrass toward the south.

The distribution of energy production by county is shown in Figure 3.4. Comparing Figure 3.4 with Figure 3.3 shows that energy production tends to be greatest in counties contributing both corn stover and switchgrass and least in counties contributing only switchgrass. Such an association between crop and energy distribution does not hold in general, however, because energy production depends on the interplay between crop-type mix, crop yields, and the amount of area available for each crop.

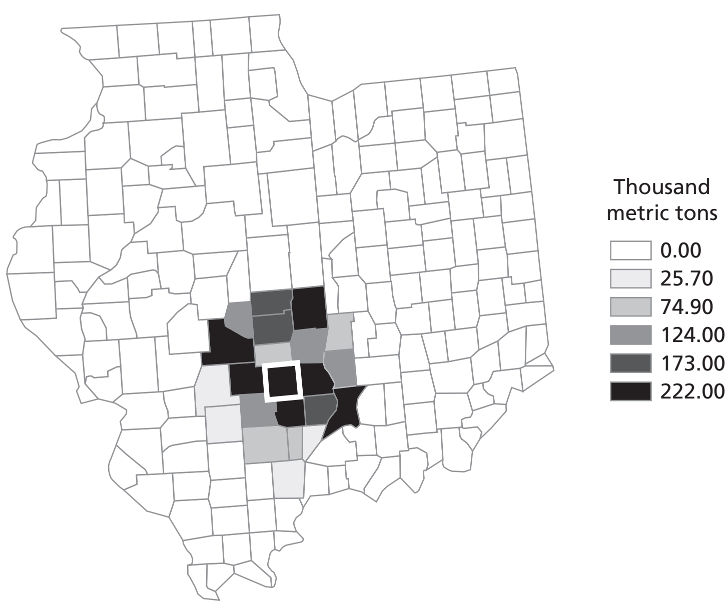
Figure 3.5 shows the distribution of different land types contributing to biomass production. This distribution is difficult to show in a map because up to four land types can contribute in each county (although only three contribute in this example). Figure 3.5 shows that 38 percent of the energy comes from switchgrass and 62 percent of the energy comes from corn stover. About two-thirds of the switchgrass comes from cropland, and about one-third

Figure 3.3
Distribution of Corn Stover and Switchgrass, by County, for Base-Case Scenario



RAND *TR876-3.3*

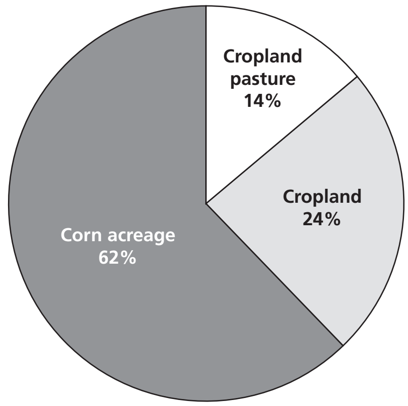
Figure 3.4
Distribution of Biomass Production, by County, for Base-Case Scenario



RAND *TR876-3.4*

comes from cropland pasture. Recall that only 10 percent of active cropland—but all cropland pasture—is available for the production of switchgrass. Switchgrass on CRP land does not appear in Figure 3.5 because it does not become cost-competitive until production exceeds

Figure 3.5
Distribution of Land Types for Base-Case Scenario



RAND *TR876-3.5*

the 3 million–ton production amount considered in this analysis. The reason it is more costly is that the yield is 10 percent lower than that on cropland, yet the land rent is nearly as high as that for cropland (see Table 3.2). Cropland pasture, in contrast, has the same yield as CRP land, but the rent is less than one-third of cropland rent.

Sensitivity of Results to Model Parameters

The base-case scenario represents our best estimates of the parameter values, but many parameter values are uncertain, either because of variability (e.g., crop yields, costs) or because their values depend on decisions about the design of a biomass production system (e.g., power-plant location, crop and land type). In this section, we present results for a range of values and conditions to explore the sensitivity of the results to different parameters.

Table 3.2
Typical Cost Elements for Base-Case Scenario Conditions ($/ton)

		Switchgrass		
Cost Element	**Corn Stover**	**Cropland**	**Cropland Pasture**	**CRP Land**
Land rent	0	18	5.0	17
Production/collection	41	33	37	37
Storage	21	20	20	20
Transportation (10 miles)	2.1	2.0	2.0	2.0
Total (10 miles)	65	73	64	76
Transportation (70 miles)	15	14	14	14
Total (70 miles)	78	85	76	88

NOTE: The 10- and 70-mile cases are summed independently.

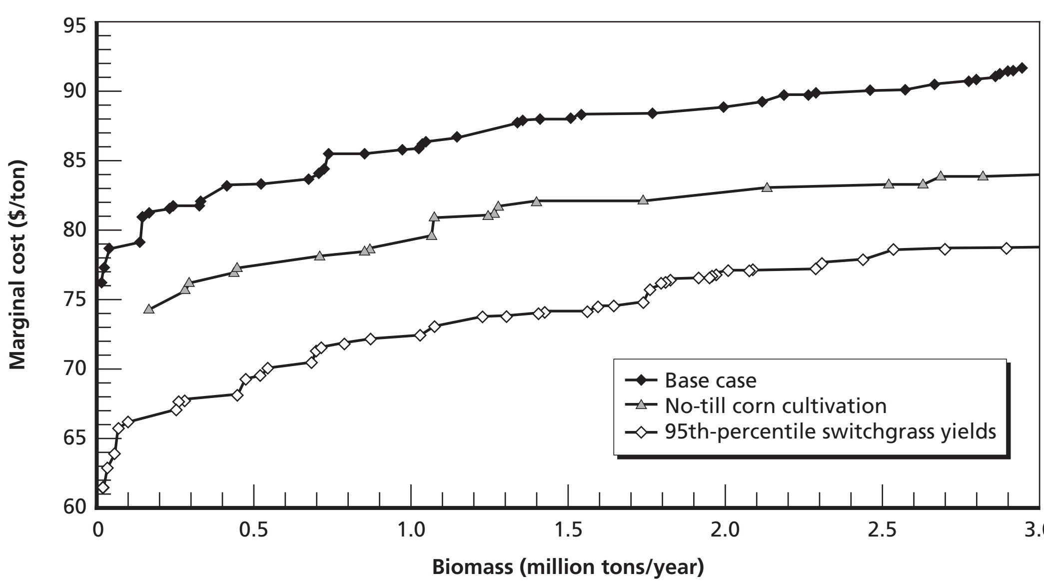
Crop Yield

An important uncertainty in our analysis is crop yield. Neither switchgrass nor corn stover has been produced at large scales in yield-limited amounts. Corn stover has long been used in limited amounts for livestock feed, but production levels have generally been far below the potential supply capacity. Consequently, modeled yield limits based on soil-moisture or wind-erosion constraints (e.g., those of Graham et al., 2007, which are used in this study) have not been tested empirically. Nearly all the switchgrass yield data available (used to calibrate the model of Gunderson et al., 2008, which we use in our analysis) are derived from test plots grown mostly for research purposes. Reliable yields for large-scale energy production operations will not be available until large-scale demonstration projects are put in place. Improvements in management practices, collection technologies, or genetic engineering will increase yields. On the other hand, greater-than-anticipated erosion, moisture loss, soil carbon loss, nutrient loss, or other limitations could limit or reduce yields.

To test the sensitivity of our results to switchgrass yields, we calculated a supply curve using the unmodified yield values from Gunderson et al. (2008). Recall that their reported values are the 95th-percentile results of their calibration data; our base case uses 70 percent of these values to approximate mean yields. To test the sensitivity to corn-stover removal rates, we calculated a supply curve using the potential removal for no-till corn production. No-till cultivation reduces moisture and erosion losses and so allows a greater fraction of the produced stover to be collected. Corn stover yields for no-till cultivation are a factor of 1.7 greater than yields for the current tillage mix (Graham et al., 2007). The results are shown in Figure 3.6.

Using no-till corn cultivation decreases costs by about \$6 per dry ton, while increasing switchgrass yields to the 95th-percentile values decreases costs by about \$13 per dry ton. Even though switchgrass yields are increased less than corn-stover yields (a factor of 1.4 for switchgrass compared to a factor of 1.7 for corn stover), increasing switchgrass yields has a greater

Figure 3.6
Supply Curves for Increased Crop Yields



RAND *TR876-3.6*

effect on cost than does increasing corn-stover yields. This occurs because switchgrass costs are much more sensitive to yield than are corn-stover costs.

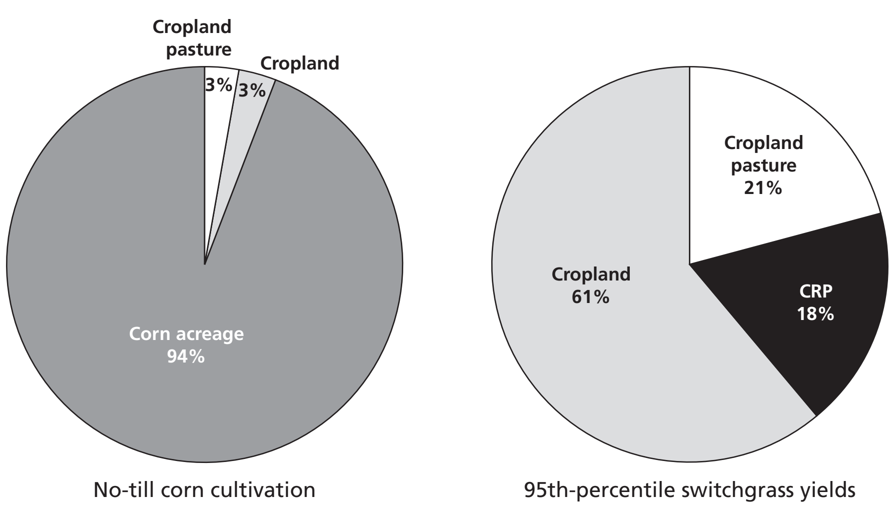
Changing yields also changes the crop distribution, because production costs depend on yield. For no-till corn cultivation, corn-stover removals increase and costs decrease, so the relative proportion of corn stover increases to 94 percent of biomass energy supplied. Similarly, using the 95th-percentile switchgrass yields results in 100-percent switchgrass (Figure 3.7), with the majority of it being grown on cropland.

Cost

Another important uncertainty in our analysis is the cost of supplying biomass. The main elements contributing to the total cost are land rent, crop production and collection, transportation, and storage. Values of these cost elements for conditions representative of the base-case scenario for the Illinois example are shown in Table 3.2. Two cases for transportation are listed in the table to indicate the dependence of cost on transportation distance. Some individual cost elements differ substantially among the crop–land type pairs, although the total costs agree with each other to within about 20 percent.

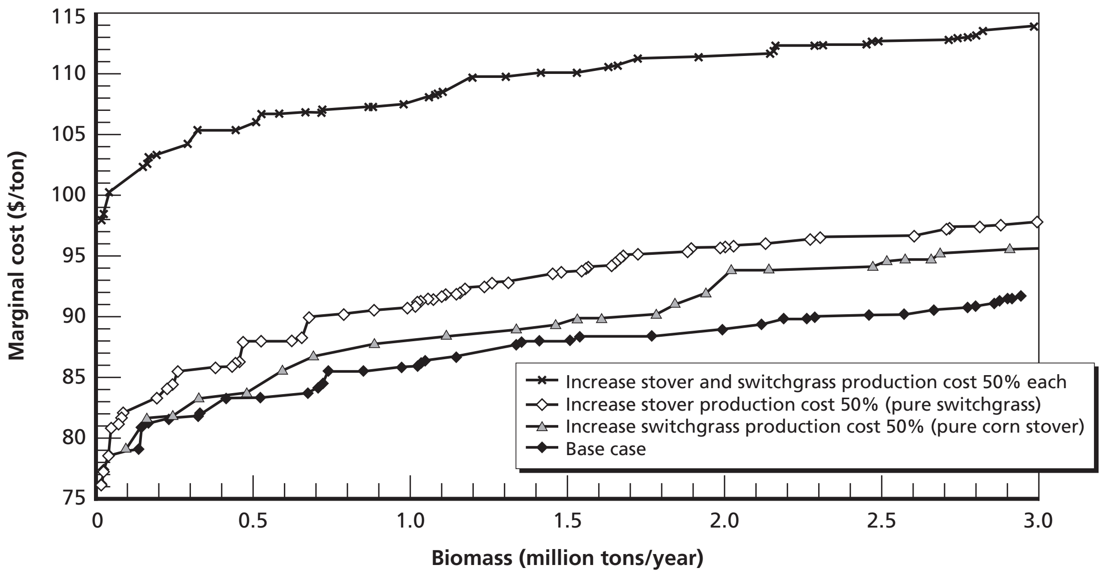
Of these cost elements, by far the most uncertain are the costs of collecting corn stover and growing and harvesting switchgrass. These are also the largest cost elements, so the total cost is most sensitive to uncertainties in them. To test the sensitivity to cost, we first increased the production cost of corn stover by 50 percent and then the cost of switchgrass by the same amount. The results are shown in Figure 3.8. Because the costs of corn stover and switchgrass are similar in the base case, the effect of increasing the cost of one crop is to shift the lowest-cost mix of crops toward the other crop. Consequently, increasing the cost of one crop has a relatively modest effect on total cost but a large effect on which crop is used for biomass. In fact, the 50-percent cost increases shown in Figure 3.8 are large enough to shift production entirely to the other crop (increasing corn-stover cost by more than 40 percent results in supplying the facility 100 percent with switchgrass, and increasing switchgrass cost by more than 45 percent results in the facility using only corn stover). Increasing the costs of both crops by

Figure 3.7
Crop Distribution for Increased Crop Yields



RAND *TR876-3.7*

Figure 3.8
Supply Curves for Increased Cost



RAND *TR876-3.8*

50 percent has a much greater effect on total cost and little effect on which crop is used compared to the base case.

Power-Plant Location

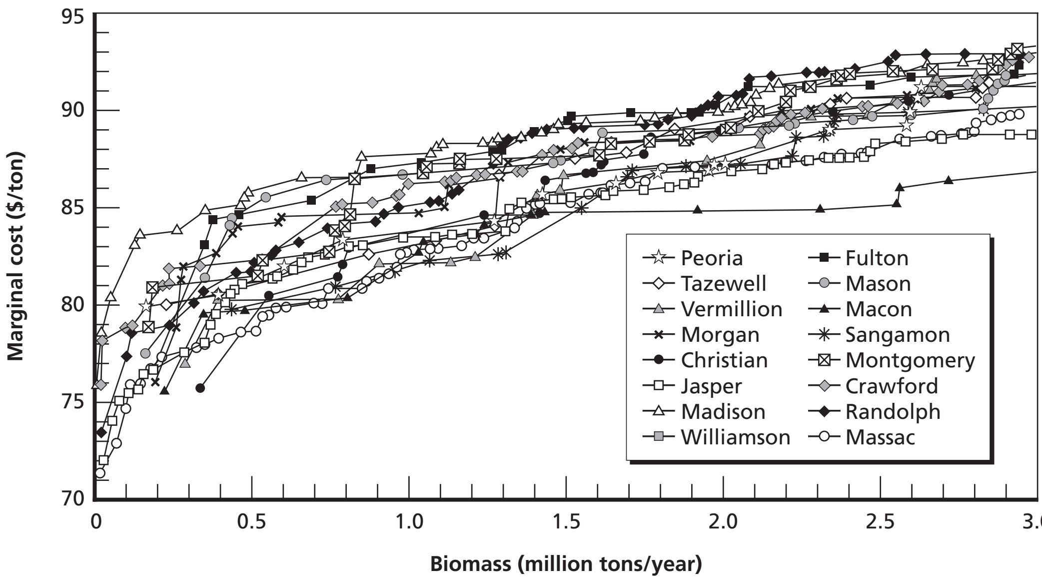
In addition to parameters subject to variability and uncertainty, the results of our analysis depend on parameters that depend on system design. One important design consideration is the location of the power plant to which the biomass fuel is being supplied. Supply curves for 16 counties containing coal-fired power plants in the southern half of Illinois are shown in Figure 3.9. The results show a relatively tight clustering, with distribution of costs spanning about $7 per dry ton. Costs show no systematic dependence on location.

Although location does not strongly influence energy cost, the relative energy contributions of corn stover and switchgrass depend strongly on latitude. Figure 3.10 shows that the distribution changes from nearly 100-percent corn stover in central Illinois to nearly 100-percent switchgrass in southern Illinois. The opposing gradients in the relative contributions of corn stover and switchgrass result from changes in yields of both crops, as well as a decrease in the amount of corn acreage toward the south. The combination of increasing switchgrass yield, decreasing corn-stover yield, and decreasing corn acreage from north to south results in the dramatic shift from one crop to the other.

Intermediate Storage

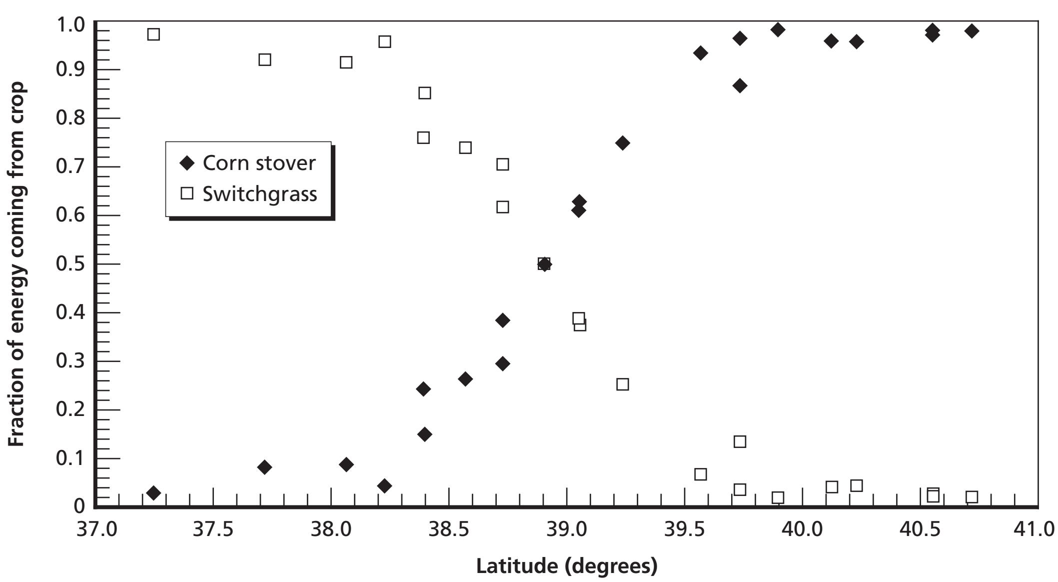
As discussed in Chapter Two, corn stover and switchgrass must be stored in order to provide a year-round supply of fuel to a power plant. In our base-case scenario, we assume that biomass is stored in dedicated storage barns. If this intermediate storage is eliminated, the total cost decreases by about $17 per dry ton, representing about 20 percent of the total plant-gate fuel cost. Although this is a relatively large effect, eliminating covered intermediate storage must be

Figure 3.9
Supply Curves for Different Power-Plant Locations in Illinois



RAND *TR876-3.9*

Figure 3.10
Relative Energy Contribution of Corn Stover and Switchgrass as a Function of Latitude



RAND *TR876-3.10*

weighed against the potential for increased costs from storing switchgrass on farms, as well as increased losses resulting from unprotected storage.

Crop and Land Type

In the base-case scenario, the units of biomass are combined in order of increasing cost without constraining the crop type, land type, or location. The lowest-cost supply curve therefore con-

sists of a mix of different crop and land types from the counties surrounding the power plant. However, crop- or land-type choices might be limited in an emerging biomass market. It is therefore instructive to examine supply curves for individual crop and land types.

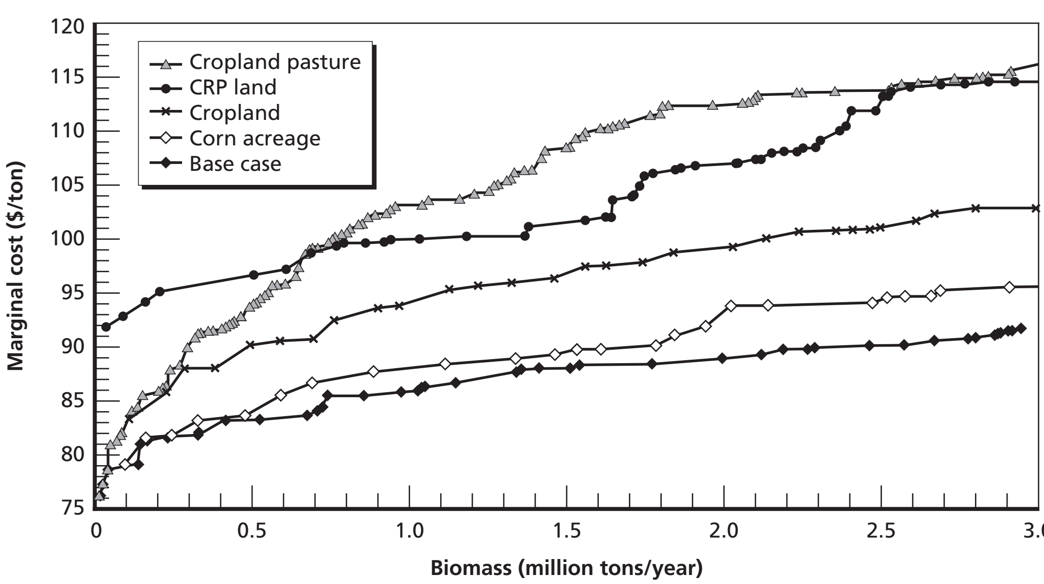
The effect of crop type can be seen in Figure 3.8. As discussed above, increasing the cost of one crop shifts production to the other, so that the supply curve when the costs of switchgrass are higher is composed entirely of corn stover and the supply curve when the costs of corn stover is higher is composed entirely of switchgrass. The cost for the base case is lower than for either corn stover or switchgrass individually because the model selects the cheaper of either corn stover or switchgrass for each production unit. The differences among the curves are relatively small because the costs of switchgrass and corn stover are similar. Producing 100-percent corn stover is at most about $4.50 per dry ton greater than the base case, and producing 100-percent switchgrass is at most about $7 per ton greater.

Supply curves for the different land types are shown in Figure 3.11. The curve for corn acreage is identical to the corn-stover curve in Figure 3.8. When restricting switchgrass production to one land type, cropland is the lowest cost. This might seem surprising given that the land value of cropland is much greater than that of cropland pasture. The reason it is less expensive overall is that switchgrass yields are higher on cropland than on cropland pasture and CRP, and that cropland is far more available, so more switchgrass can be grown closer to the power plant, reducing transportation costs relative to cropland pasture or CRP land. Based on the results in Table 3.2, the difference in land rent between cropland and cropland pasture when growing switchgrass is offset when the switchgrass is grown on cropland at least 45 miles nearer to the plant than the cropland pasture.

Charges for Greenhouse-Gas Emissions and Carbon Credits

An important influence on the costs and crop and land choices for biomass fuel production is potential charges for GHG emissions or credits for storing carbon in the ground. Our base-

Figure 3.11
Supply Curves for Different Land Types



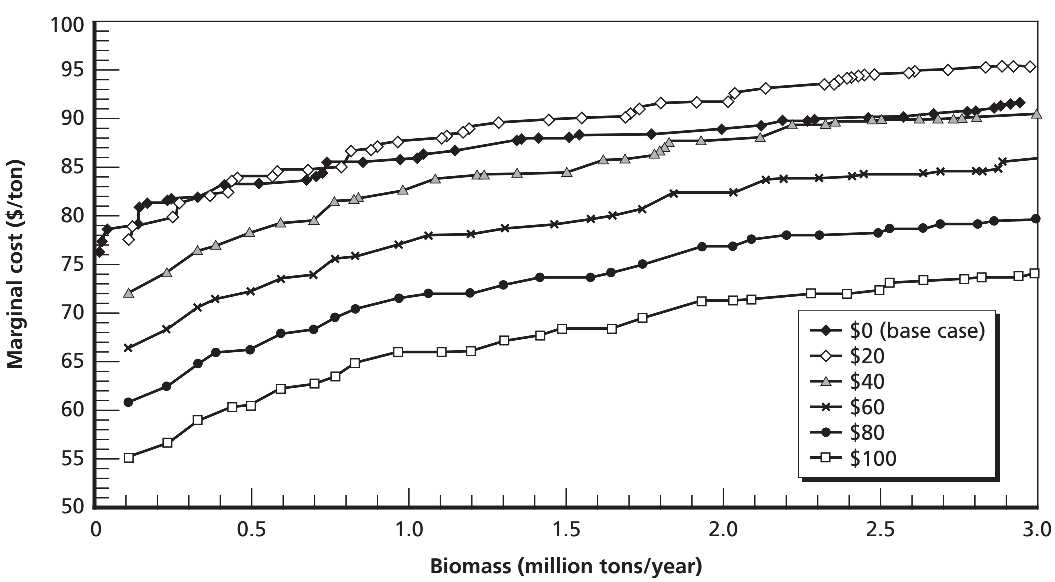
RAND *TR876-3.11*

case scenario does not include these policies because there currently is no legislation in effect that pertains to agriculture.

Estimates of life-cycle GHG emissions associated with producing biomass energy exist and can be applied to our analysis (e.g., Curtright et al., 2010). These estimates allow us to estimate GHG emissions and carbon storage associated with corn-stover and switchgrass production. As discussed in more detail in Chapter Two, the life-cycle GHG emissions from biomass production are dominated by soil carbon emitted or sequestered due to land-use changes. Other sources of GHG emissions from the production of biomass energy crops include exhaust from farm machinery and trucks used for transportation and emissions of nitrous oxide resulting from the application of fertilizer. As emphasized in Chapter Two, the life-cycle GHG emissions modeled here include only those resulting from direct land-use changes. Collecting corn stover for biomass energy results in a net removal of soil carbon and hence more carbon dioxide in the atmosphere. In the case of switchgrass, life-cycle GHG emissions depend on the land type and prior land use. Switchgrass grown and harvested on cropland pasture or CRP land results in a net removal of soil carbon from land that otherwise would not have anything removed from it, resulting in higher concentrations of greenhouse gases in the atmosphere. On the other hand, switchgrass grown on cropland replaces row crops that typically deplete soil carbon, thereby resulting in a net sequestration of carbon in the soil. In this case, the net GHG emission reflects the balance between the negative contribution from carbon sequestration and the positive contribution from vehicle emissions. These net emissions are always negative because the mass of sequestered carbon dwarfs the mass of carbon from vehicle emissions.

To analyze the potential effects on the provision of biomass to a cofired power plant, we use a range of potential charges on carbon dioxide emissions, ranging from \$20 per metric ton of carbon dioxide equivalent to \$100 per metric ton, as shown in Figure 3.12. Total production costs initially increase and then fall sharply when charges for emissions of GHG are higher. This behavior reflects a trade-off between using cropland pasture, which has lower production

Figure 3.12
Supply Curves for Different Carbon Charges



RAND *TR876-3.12*

costs but would result in emitting GHGs, and cropland, which has higher production costs but would store more carbon if switchgrass replaced the cultivation of other crops. At $20 per metric ton of GHG emissions, biomass is supplied using substantial amounts of both cropland pasture and cropland; the total cost is slightly higher than in the base case. The increase in cost relative to the base case indicates that the savings from sequestering more carbon in the soil on cropland are not enough to overcome the higher production costs on cropland. As the charge on GHG emissions increases, credits for sequestering carbon in the soil increase and surpass the production cost savings on cropland pasture. Consequently, the crop distribution shifts toward cropland until all production is on cropland by the time the charge on GHG emissions reaches $80 per metric ton.

Summary of Sensitivity Analyses

The cost of supplying biomass energy and the distribution of crop and land types in producing that supply depends on several factors. These factors can be separated into those whose uncertainty stems primarily from incomplete data and variability in the weather and prices and those that will vary with the production system design. The results of our sensitivity analyses are summarized in Table 3.3. The average cost is the average unit cost for all of the supply

Table 3.3
Summary of Sensitivity Analyses

Scenario	Average Cost ($/ton)	Average Cost ($/GJ)	Harvested Area (million acres)	Fraction of Energy from Switchgrass
Base case	87	5.12	1.9	0.37
95th-percentile switchgrass yields	74	4.36	0.36	1.0
No-till corn cultivation	81	4.76	1.5	0.06
Increase stover production cost 50%	93	5.45	0.51	1.0
Increase switchgrass production cost 50%	90	5.29	2.7	0.00
Increase both production costs 50%	110	6.44	1.5	0.51
Power plant in central Illinois	86	5.06	2.4	0.02
Power plant in southernmost Illinois	84	4.94	0.55	0.97
No intermediate storage	70	4.10	2.0	0.34
Corn stover only	90	5.29	2.7	0.00
Switchgrass only	93	5.45	0.51	1.0
Supply from corn acreage only	90	5.29	2.7	0.0
Supply from cropland only	96	5.66	0.49	1.0
Supply from cropland pasture only	105	6.20	0.53	1.0
Supply from CRP land only	104	6.12	0.54	1.0
Carbon cost = $20/metric ton CO_2e	89	5.26	0.49	1.0
Carbon cost = $100/metric ton CO_2e	67	3.97	0.49	1.0

NOTE: CO_2e = carbon dioxide equivalent.

units contributing to the supply curve and hence is equivalent to the actual cost for the entire 3 million–ton supply.

Factors that are uncertain because of variability include crop yields and costs. In addition, there is substantial uncertainty concerning potential yields for switchgrass and corn stover in the event of substantial demand for energy. Agronomists are unsure of the potential for improvements in yields as seed varieties and management practices evolve. Yield estimates for best-case conditions are about 40 percent and 70 percent greater than our base-case assumptions for switchgrass and corn stover, respectively. Improvements in yields on this order would reduce total supply costs by about 17 percent and 10 percent for switchgrass and corn stover, respectively. Estimates of costs for switchgrass production and harvesting and corn-stover collection are subject to some margin of error. Production costs account for about half of the total supply cost, so, if production costs for both crops change, total supply costs change by about half as much as the production cost. Because costs of corn stover and switchgrass are similar to each other, increasing the cost of one shifts production to the other crop with relatively little change in total cost.

Factors that vary with system design include power-plant location, the use of intermediate storage, crop- and land-type constraints, corn-tillage type, and GHG emission charges and carbon credits. Within central and southern Illinois, the location of the power plant has a relatively small effect (approximately plus or minus 5 percent) on energy cost. Location has a significant effect on crop distribution, which shifts from nearly pure corn stover in central Illinois to almost totally switchgrass in southern Illinois. Intermediate storage is important for providing a steady stream of fuel from crops that are harvested once or twice per year. Eliminating intermediate storage would reduce total costs by about 20 percent. However, without intermediate storage, biomass would need to be stored on farms or at power plants, which would entail some costs. Hence, eliminating intermediate storage might actually only transfer costs elsewhere without reducing total costs. Because corn-stover and switchgrass costs are similar, restricting production to one crop or the other has a relatively small effect on total cost (less than 7 percent). Restricting switchgrass production to a particular land type could have a more-substantial effect on costs. Restricting switchgrass production to cropland pasture or CRP land can increase supply costs by as much as 21 percent, primarily because the area of these lands is limited, resulting in greater transportation distances and costs. Finally, GHG emission charges or credits for carbon storage can have a large effect on both total supply cost and crop and distribution of production by land type. As carbon charges increase, supply shifts entirely to switchgrass on cropland.

Because the model addresses information and implications that are specific to particular localities, the analysis presented above focuses on a specific location. However, the model contains data for the entire continental United States, and similar analyses can be conducted for any location of interest. Land rents, areas of different types of farmland, and crop yields differ considerably around the country. Given the location-specific details of the model, it is difficult to know the extent whether the results and sensitivities identified in our example application in Illinois are generalizable to other locations.

CHAPTER FOUR

Implications for Potential Investors in Power Plants Using Biomass

This chapter describes some sensitivity analyses of our model of biomass resources as they might apply to the problem of planning for biomass supply to an energy facility. Specifically, it illustrates the changes in crops, costs, geographic area over which biomass would be collected, acreage that would need to be harvested to supply the biomass, and type of land used under conditions when biomass yields vary from the assumed values and when charges are imposed on GHG emissions. The implications of variability in cost and supply area have substantial implications for alternative biomass energy applications: cofiring with coal to produce electricity, cogasifying with coal to produce liquid fuels, or biomass-only applications for electricity and liquid fuels. Cofiring applications, due to their inherent flexibility, might be able to adapt better to the potential variability of supply and price of biomass within a region. We note that the model does not include an estimate of plant handling and processing charges associated with grinding herbaceous biomass in preparation for gasification or combustion in certain applications. The general method is drawn from McGowan (2009, Chapter 10).

Overview of Plant

We examine the case of supplying a power plant with 3 million dry tons of biomass per year (about 50 million GJ per year). This would be sufficient to fuel a 500–600 MW power plant entirely on biomass or to replace one-third of the coal in a cofiring arrangement at a 1,500 MW power plant. Assuming that a plant operates at a capacity factor of 85 percent, an average of 9,700 dry tons of biomass would be delivered to the plant each day.

A truckload of 42 bales of corn stover or switchgrass has a mass of approximately 20 tons. Assuming that biomass has a moisture content of 15 percent, this is approximately 17 dry tons of biomass. To supply biomass to such a facility would require approximately 570 truckloads per day. Florida Crystals operates a biomass-fueled steam and electricity plant in Okeelanta, Florida, that receives approximately 100 trucks per day (Cepero, 2009). Unloading trucks of baled biomass requires approximately 20 minutes. Assuming a similar throughput, the model facility would require eight receiving stations to meet its demand.

Alternative transportation options might be sought. For example, large-scale coal-fired energy facilities typically have access to rail freight or inland waterways. Although these modes have the advantage of significantly increased capacity, they do not obviate the need to truck the biomass from the farm to a transshipment facility.

Description of Cases

Case 1: Base Case

This case uses default parameters for the biomass supply model to estimate the costs, amount of supply, and crops that would be delivered to the energy facility. This is the same as the base case described in Chapter Three and summarized in Table 3.1.

Case 2: Low–Switchgrass Yield Case

In this case, the switchgrass yield is reduced 20 percent from the default value. Switchgrass yield depends greatly on rainfall, so this case represents the yield that could be expected in drier areas or during drier years. Lower yields will increase the cost of production of switchgrass, resulting in greater use of corn stover. The marginal price of biomass will increase, but not significantly.

Case 3: Low–Corn-Stover Yield Case

In this case, the amount of corn stover that can be collected is reduced by 20 percent. As discussed earlier, the amount of corn stover required to be left on the field to prevent erosion, moisture loss, and soil carbon depletion is highly uncertain. In addition, corn stover left on the field provides some essential nutrients that would need to be replaced when stover is collected. A portion of the nitrogen in fertilizer applied to corn disassociates into nitrous oxide. Nitrous oxide is a potent greenhouse gas with a global warming potential 300 times that of carbon dioxide (Intergovernmental Panel on Climate Change, 2007). The amount of nitrous oxide that enters the atmosphere as a result of fertilizer application is particularly uncertain, but can be significant. In this case, we would expect the complementary result of case 2—namely, decreased sourcing of corn stover at slightly increased prices over the base case.

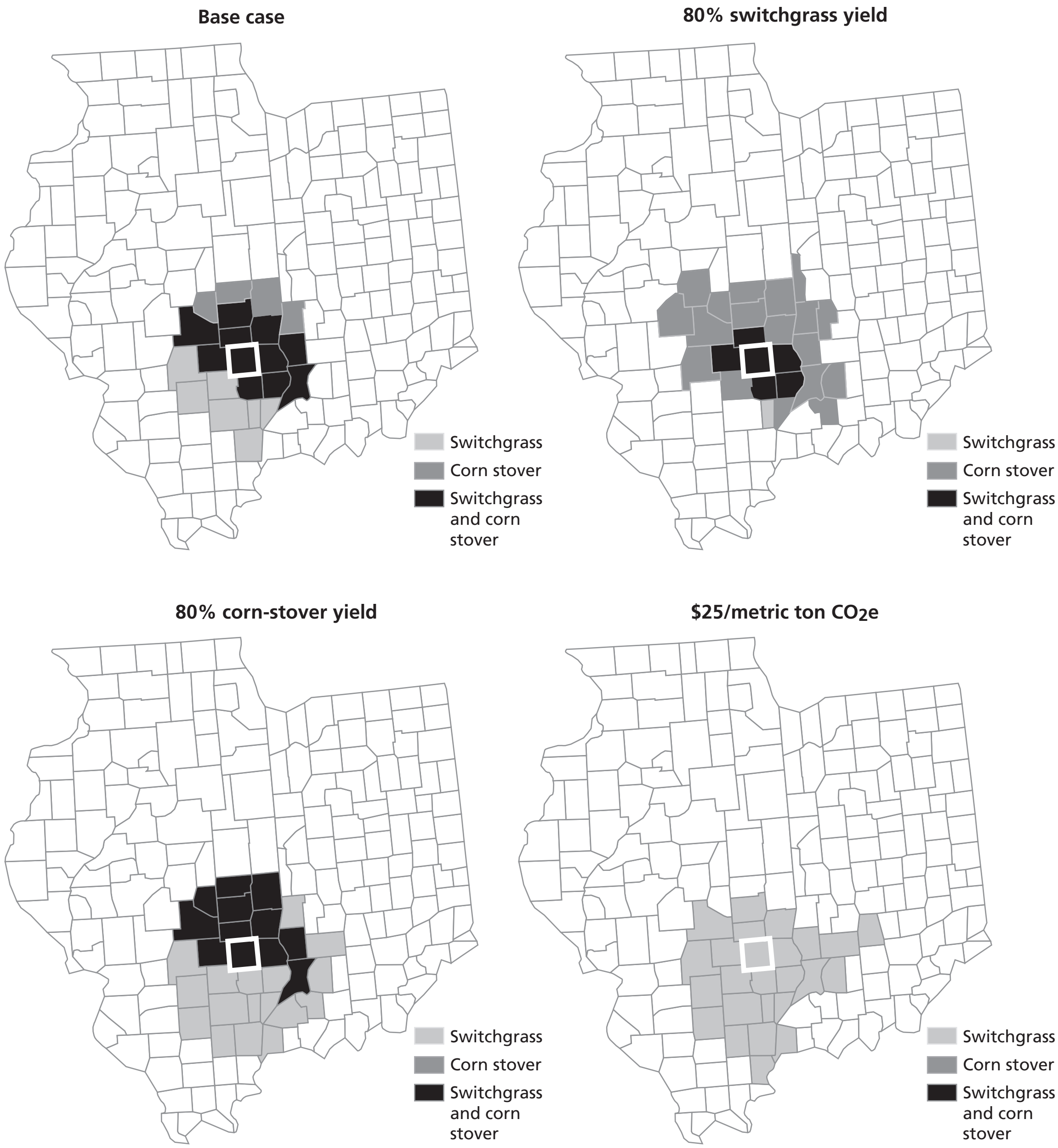
Case 4: $25 Carbon Dioxide Case

In this case, we assume the federal government imposes a $25-per-metric-ton of CO_2e charge on GHG emissions. Such a charge would heavily favor switchgrass, if it recognizes changes in carbon storage in the land used to produce the crop. This is because collecting corn stover results in much greater carbon emissions through removal of soil carbon compared to cultivating and harvesting switchgrass. Because switchgrass production emits less carbon than traditional food crops, replacing food crops on active cropland with switchgrass results in a net decrease in carbon emissions. We would therefore expect the imposition of a charge on GHG emissions or credit for carbon storage to result in some changes in land use.

Results

Figure 4.1 illustrates types and location of crops produced to supply the energy facility under the four cases. In this illustration, the plant is located in Jasper County, which is outlined in white. In the base case, counties in the northern part of the supply area supply corn stover, counties in the central part supply both corn stover and switchgrass, and counties to the south supply solely switchgrass. Biomass must be collected from catchment area of 22 counties (a collection radius of about 70 miles), and biomass is harvested on 1.9 million acres of farmland. Under lower switchgrass yields, the supply area shifts to the north, with most counties sup-

Figure 4.1
Biomass Crops Produced Under the Four Cases



RAND *TR876-4.1*

plying only corn stover. Only counties very close to the plant, where transportation costs are lowest, supply switchgrass. The catchment area (25 counties) and harvested area (2.6 million acres) are greater. Under lower corn-stover yields, switchgrass is supplied from all counties, including some additional surrounding counties, while corn stover is again supplied from several counties to the north. In this case, the catchment area again increases to 29 counties, while the harvested area decreases to 1.7 million acres. In the case in which a charge of $25-per-ton of CO_2e emissions is imposed, the costs of producing corn stover increase significantly, driving

production entirely to switchgrass, nearly 90 percent of which is grown on cropland, where replacing food crops with switchgrass results in a net sequestration of carbon in the soil. The catchment area is 25 counties, and the harvested area is only 0.49 million acres. Across the four cases, the catchment areas are made up of 35 different counties that shift as the parameters are varied.

Figure 4.2 indicates the amount of energy that is supplied from each county under the four cases. The shadings represent the total amount of biomass energy supplied. When switchgrass yields are reduced, the biomass supply shifts to corn stover in counties to the north of Jasper County, in which corn-stover yields are relatively higher. When corn-stover collection levels drop, it is economically preferable to grow switchgrass and there is an increase in the proportion of switchgrass grown on cropland relative to the base case. When a charge of $25 per ton of CO_2e is imposed, most production shifts to the south, where switchgrass yields are higher.

Figure 4.3 illustrates the range of costs of supplying biomass energy to the energy facility. The highest costs tend to be in outlying counties due to the increase in transportation cost with distance. This general trend does not always hold, however, because of variations in land availability and rents. In the base case, the costs range from $76 to $89 per dry ton ($4.50 to $5.35 per GJ), with an average cost of $86 per dry ton. When switchgrass yields decrease, the cost of supplying biomass energy is nearly unchanged (average cost increases 2 percent to $88 per dry ton) even though the crop type has shifted almost entirely to corn stover. Similarly, when corn-stover yields decrease, production shifts toward switchgrass but the cost increases only 3.5 percent, to $89 per dry ton. When a $25 charge for emitting a metric ton of CO_2e is imposed, the ability of switchgrass to sequester carbon in the soil results in a credit that reduces costs for switchgrass grown on cropland. In this case, production shifts entirely to switchgrass, more than 90 percent of which is grown on cropland, and the cost of supplying biomass to the facility is $88 per dry ton.

The results for the four cases are summarized in Table 4.1.

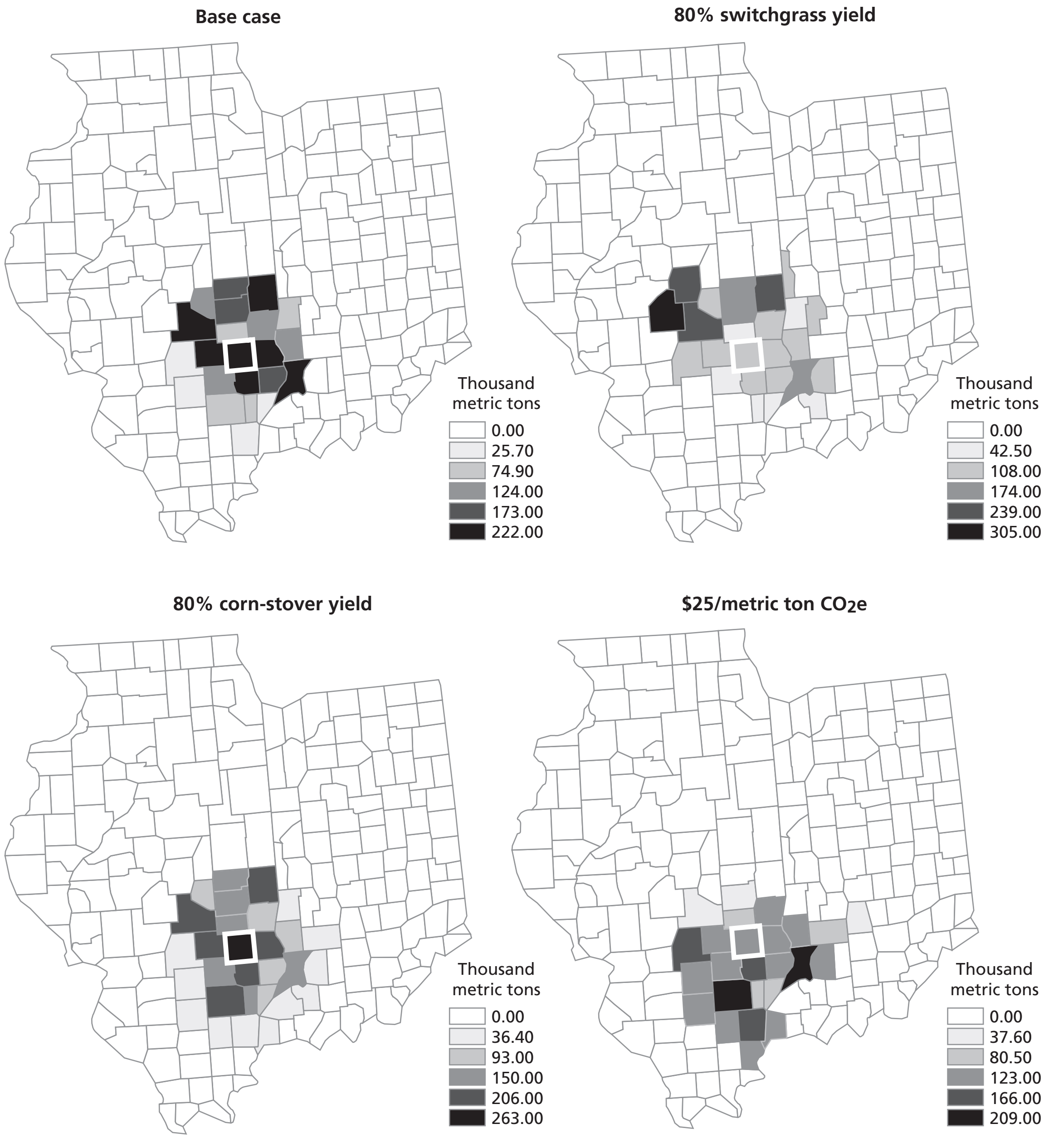
Implications for Potential Investors in Biomass Facilities

The results indicate some potential general lessons for supplying biomass to energy facilities in the corn belt. Here we discuss three important implications of our analysis: the effect of uncertainty and variability in crop yields on the distribution of crop and land types for supplying biomass, the effect of carbon pricing on biomass crop and land types, and the amount of agricultural land required to supply biomass energy. Because the model is sensitive to local details, these lessons strictly hold only for the corn-belt region. The model can be run for any location in the continental United States, and results for other locations could lead to different insights about biomass energy supply.

Effect of Crop Yields on Biomass Supply

In our analysis, the plant-gate cost of biomass does not vary significantly because of differences in crop yields. This is because corn stover and switchgrass have similar production and delivery costs and can, purely from a cost perspective, easily substitute for one another. However, this substitution strongly influences the amount of farmland required to supply a given amount of biomass and can also strongly affect the geographic area from which biomass is supplied.

Figure 4.2
Biomass Energy Supplied to a Jasper County Energy Facility Under Four Cases

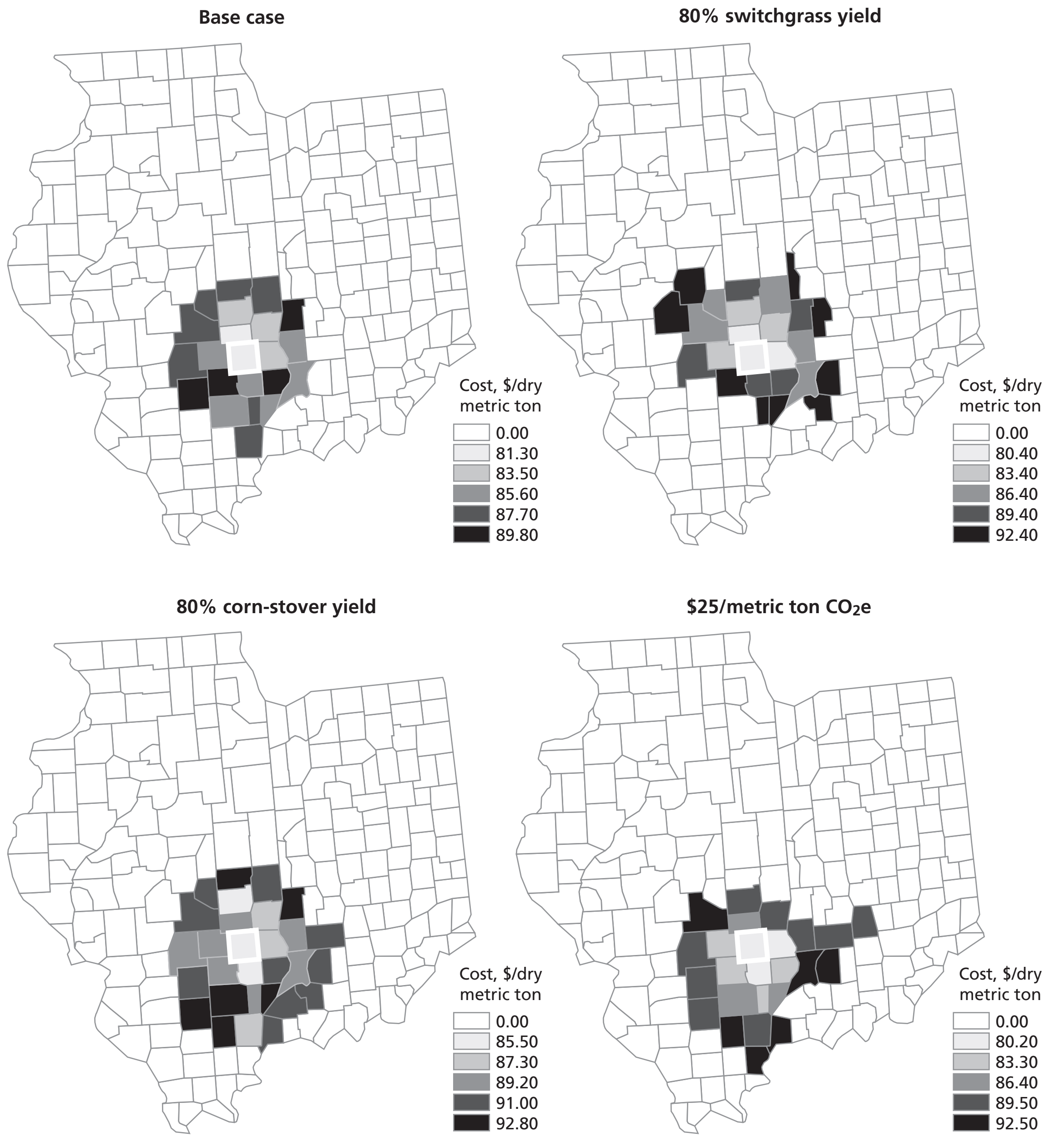


NOTE: Legend indicates midpoint of value range.
RAND *TR876-4.2*

The variation in the amount of farmland required results from the fact that switchgrass yields are much higher than corn-stover yields. Supplying energy from corn stover in Illinois requires approximately five times as much farmland as supplying the same amount of energy from switchgrass. This effect is even more dramatic in other parts of the country where corn yields are lower and a smaller fraction of the stover can be removed.

The variation in the geographic area from which the lowest-cost biomass is supplied results primarily from spatial variations in yields. In the area around our model facility, opposing gradients in yields for switchgrass and corn stover with latitude cause corn stover to be drawn from the north and switchgrass to be drawn from the south. Interestingly, even though corn stover requires five times more farmland than switchgrass, the overall geographic area required

Figure 4.3
Cost of Biomass Energy Supplied to a Jasper County Energy Facility for Four Cases



NOTE: Legend indicates midpoint of value range.
RAND *TR876-4.3*

Table 4.1
Summary of Results for Plant Planning Example Cases

	Case 1	Case 2	Case 3	Case 4
Number of counties required	22	25	29	25
Harvested area (million acres)	1.9	2.6	1.7	0.49
Fraction of energy from switchgrass	0.38	0.02	0.57	1.0
Average cost per ton	$86	$88	$89	$88

for supplying corn stover is actually somewhat smaller than that for switchgrass because there is much more land available for producing corn stover than for switchgrass.

Our results indicate that, in the absence of carbon pricing, relatively small variations in crop yields can result in substantial changes in the amount, type, and spatial distribution of land that would produce the lowest-cost biomass for an energy facility. Conditions affecting yields could vary annually, making it difficult to predict what and where the most cost-effective biomass sources will be. Such uncertainty might make it difficult to establish reliable, long-term relationships between biomass suppliers and consumers, particularly in the early stages of development of a biomass energy market. Consequently, plant operators might choose to arrange to procure biomass from a wide range of suppliers in the vicinity of their facility to hedge against potential shifts in production and changes in costs.

In light of this uncertainty, if the goal of early biomass supply efforts is to gain experience sourcing, handling, and processing biomass, then it might be most effective to concentrate on corn stover. Corn stover is produced in any case and is already large available. If a facility encounters excess supply of biomass, it is likely to be less costly to not harvest corn stover in a given year than not purchase a crop of switchgrass that has been planted. A corn farmer might be able to weather a decision by the plant not to purchase corn stover better than a farmer who has planted switchgrass could withstand a plant decision not to buy switchgrass. However, such an approach should take into account potential long-term implications of increased emissions of carbon dioxide from the soil that result from the removal of corn stover.

Effects of a Charge on Greenhouse-Gas Emissions or Carbon Credits for Biomass Supply

Land and crop choices would be very sensitive to policies governing GHG emissions and carbon charges or credits. When no charges are in place, the lowest-cost biomass is a mix of corn stover, switchgrass grown on cropland pasture, and switchgrass grown on cropland. As carbon charges and credits increase, the lowest-cost biomass source rapidly shifts toward switchgrass grown on cropland. The lowest-cost source mix of biomass could therefore change dramatically if charges on GHG emissions come into play, introducing additional uncertainty about what crops and lands would be used to produce biomass. Although the magnitude of this effect might vary with location, the general trend of carbon pricing driving biomass production toward cropland is anticipated to be a general result that holds for all locations.

If emission charges and carbon credits shift energy crop production to cropland, energy crops will increasingly compete with food crops for land. This will result in decreased food crop production, increasing food crop prices, which could ultimately lead to national and international deforestation to replace food crops displaced by biomass production. The life-cycle GHG emissions calculations used in our analysis (from Curtright et al., 2010) do not

account for emissions from such indirect land-use changes. Accounting for such effects is difficult because of the uncertainty in predicting the magnitude and because it essentially makes biomass producers responsible for environmental consequences of remote decisions over which they have no control (Searchinger et al., 2008; Kim, Kim, and Dale, 2009). The complexity of the trade-off between the effects of direct and indirect land-use change demonstrates that the relative attractiveness of different biomass sources is quite sensitive to the extent of environmental impacts accounted for in the analysis (Scharlemann and Laurance, 2008). If calculations of GHG emissions associated with switchgrass production include both local carbon retention and indirect carbon emissions from deforestation, the cost advantage of growing switchgrass on cropland is diminished and might favor energy crop production on degraded lands, which would have no effect on food production.

Land Area Required to Sustain Biomass Energy

Our analysis focused on fueling an individual power plant and indicates that 3 million tons of biomass, which would fuel about 500 MW of electrical generating capacity, could be produced by growing switchgrass on 0.5 million acres or harvesting stover from 2.7 million acres of corn (Table 3.3). Extrapolating this calculation to the state level shows that fueling electricity generation with biomass would require substantial amounts of land. About half of the electricity generated in Illinois comes from coal-fired power plants (EIA, 2011b). Coal plants in Illinois consumed 57 million short tons of coal in 2008 (EIA, 2011c), equivalent to 1.1 billion GJ (EIA, 2011a). To replace 25 percent of the coal currently used at each of the state's 24 coal-fired power plants with biomass, 12 million acres would be needed, more than 90 percent of which would be corn acreage producing corn stover. The total corn acreage in Illinois in 2007 was 13 million acres (USDA, 2009). Hence, fueling one-eighth of the total electricity generation in Illinois with biomass would require harvesting corn stover from nearly all of the corn grown in the state. No-till corn-cultivation practices increase the amount of stover that can be sustainably harvested, which would reduce the area from which stover would need to be collected by about 30 percent.

Restricting the biomass supply to switchgrass only would reduce the required land area to 3.2 million acres, consisting of 1.3 million acres of active cropland and 1.9 million acres of cropland pasture and CRP land. With a total of 23 million acres of actively harvested cropland in Illinois (USDA, 2009), 6 percent of food crop production would be displaced to supply enough switchgrass to fuel one-eighth of total electricity generation.

Agricultural productivity in Illinois, in terms of both land area allocated to agriculture and crop yields, is among the highest in the nation. Our findings about the large amount of land required to support biomass energy production therefore only become more pressing in other parts of the country.

Such high land requirements would likely raise questions about environmental implications, implications for transportation, and workforce requirements of biomass production. In addition, the land requirements for each power plant were calculated independently even though the catchment areas for many of Illinois's coal-fired power plants would overlap. This means that the actual transportation distances would be greater and costs higher than calculated with our model. Competition for limited biomass resources among power plants would drive up prices. Competition for land with food crops would also push up prices. Although current production costs are far too high to stimulate unsubsidized biomass production, these

factors demonstrate the complexity in estimating the true costs and land requirements of a functioning biomass fuel market.

Switchgrass and Corn-Stover Production Costs

Production costs for switchgrass and corn stover were calculated drawing on parameter estimates from the recent literature. For switchgrass, the costs of establishing a stand are amortized over ten years. For stover, differing collection methods lead to different cost curves depending on the percentage of stover that might be collected from a field.

Switchgrass Production Costs

Switchgrass production costs consist of the costs of seed, fertilizers and herbicides, and machinery operation to prepare for, plant, and harvest the crop. We use the cost estimates by Khanna, Dhungana, and Clifton-Brown (2008), who calculated switchgrass production costs for Illinois. Their final results also include land-use cost and transportation, which we exclude because these are costs we estimate separately. Units are converted from dollars per acre to dollars per hectare. Finally, dollars are adjusted from 2003 dollars to 2008 dollars by multiplying by the ratio of the Farm Price Index for these years, 149/106 (National Agricultural Statistics Service, 2009). This gives production costs per acre; dividing by the yield per acre gives costs per ton of switchgrass.

One of the parameters determining production costs is the length of time in which the farmer will recover his or her fixed initial costs of establishing the switchgrass. We use ten years in our analysis, which is consistent with Khanna, Dhungana, and Clifton-Brown (2008); Perrin et al. (2008); and Duffy (2008). In order to calculate the costs for differing lengths of time, we reconstruct Khanna, Dhungana, and Clifton-Brown's methods. Costs in the first year (in 2003 dollars per acre), $270.47, are amortized over the entire period. Costs in the second year, when herbicides are still used and there is a 25-percent probability that reseeding will be required, are $282.80 and are amortized over one fewer years. Subsequent annual costs are $344.88. The discount rate used is 4 percent, following Khanna, Dhungana, and Clifton-Brown (2008). Duffy (2008) uses an 8-percent discount rate.

Using these parameters, we calculate the cost per ton of producing switchgrass according to the following equation. Note that this does not include land rent costs.

$$\text{Cost}_{\text{switchgrass production}}\left(y,t\right)=\begin{pmatrix}\$270.47\dfrac{.04}{1-1.04^{-t\text{ years}}}+\\ \$282.80\dfrac{.04}{1-1.04^{-(t\text{ years}-1)}}+\$344.88\end{pmatrix}\times\ \frac{1}{y\text{ tons/acre}}\times\frac{149}{106},$$

where t is the number of years over which costs are spread (amortized) and y is the yield of switchgrass in tons per acre.

Corn-Stover Production Costs

Corn-stover production costs are assumed to include only the costs of harvesting stover. All other costs of planting and raising the crop are attributed to the corn grain, rather than the stover, as is consistent with our premise that only land currently growing corn will be used to produce stover. The amount of stover removed will be limited by concerns about the effects that removing stover could have on erosion, soil moisture, and soil quality. Because of this concern, the amount of stover collected is less than the amount produced on the land.

Our source for stover collection costs is Graham et al. (2007), who derive the cost relationships from Sokhansanj and Turhollow (2002), Perlack and Turhollow (2003), and Sokhansanj, Turhollow, Cushman, and Cundiff (2002). Costs per ton include the cost of nutrient replacement and depend on the amount of stover collected. For different ranges of collected stover quantity, different equipment types are used. For the lowest-yield land, a combine spreader is used to move the stover into windrows, which are then collected into round bales by a tractor. For collecting more than 1.2 tons per acre but less than 1.5 tons per acre, a similar method is used with an additional tractor attachment, a front-end wheel rake, when making windrows. For higher collected yields, a different process is used: flail-shredding and raking, and subsequent baling. Costs per unit tend to decrease as the amount collected increases, although there is an initial increase in costs when shifting to the flail-shredding/raking and baling method. The cost equations for each of these processes are directly from Graham et al. (2007), with unit conversions from metric tonnes (megagrams, Mg) to tons and from hectares to acres. Dollars are then converted from the 2002 dollars used by Graham et al. (2007) to 2008 dollars using the ratio of the Farm Price Indices from these years, 149/98 (National Agricultural Statistics Service, 2009). The final equations are as follows, with y representing tons of stover collected per acre:

If collecting less than 1.2 tons/acre,

$$\text{Cost}_{\text{stover}<1.2\text{ tons/acre}}(y) = 51.72 \times \left(y \text{ tons/acre} \times \frac{2.47 \text{ acres}}{1 \text{ hectare}} \times \frac{0.907 \text{ Mg}}{1 \text{ ton}} \right)^{-0.56} \times \frac{149}{98} \times \frac{0.907 \text{ Mg}}{1 \text{ ton}}.$$

If collecting between 1.2 and 1.5 tons/acre,

$$\text{Cost}_{1.2\text{ tons/acre}<\text{stover}<1.5\text{ tons/acre}}(y) = 48.01 \times \left(y \text{ tons/acre} \times \frac{2.47 \text{ acres}}{1 \text{ hectare}} \times \frac{0.907 \text{ Mg}}{1 \text{ ton}} \right)^{-0.45} \times \frac{149}{98} \times \frac{0.907 \text{ Mg}}{1 \text{ ton}}.$$

If collecting more than 1.5 tons/acre,

$$\text{Cost}_{\text{stover}>1.5\text{ tons/acre}}(y) = 50.65 \times \left(y \text{ tons/acre} \times \frac{2.47 \text{ acres}}{1 \text{ hectare}} \times \frac{0.907 \text{ Mg}}{1 \text{ ton}} \right)^{-0.41} \times \frac{149}{98} \times \frac{0.907 \text{ Mg}}{1 \text{ ton}}.$$

Costs of Transporting and Storing Biomass

Our estimate for transporting and storing baled switchgrass and corn stover is based on custom rates for agricultural services and recent experience with storing switchgrass.

We assume that the harvested biomass is baled into large rectangular dimensions (4 feet by 3 feet by 8 feet). Corn stover has a slightly lower bulk density than does switchgrass. The mass of a bale of corn stover was estimated from Sokhansanj, Turhollow, Cushman, and Cundiff (2002), who reported a mass of 1,200 pounds per 4-foot by 4-foot by 8-foot bale, or 900 pounds per 4-foot by 3-foot by 8-foot bale. The mass of a bale of switchgrass is estimated to be 950 pounds, which is slightly lower than the average bale weight reported by the Chariton Valley Biomass Project (Antares Group, 2009, pp. 5–29).

Bales are assumed to be transported on 56-foot flatbed trailers in loads of 42 bales (Antares Group, 2009, Exhibit 16). The mass of a full load of bales is 18.9 tons for corn stover and 20.0 tons for switchgrass. According to the 2008 Nebraska custom rate survey (Jose and Janousek, 2010), the per-mile rate for transporting a full load of large rectangular bales ranges from $1 to $11, with a most-common rate of $4. We normalize these rates by the mass of a load to derive a rate per ton-mile. The model looks up the highway distance between the county of production and the county in which the plant is located and derives a per-ton and a per–energy content cost of transportation based on the mass of the bale and the rates quoted above. Nominal (i.e., most common) rates are carried through in the analysis.

We assume that biomass is stored prior to use. The cost of storage is the sum of the costs of building and operating the storage barn, and loading and unloading the bales from the flatbed trailer. As part of the Chariton Valley Biomass Project, a series of storage sheds were constructed to store bales of biomass in anticipation of burning. The cost of construction of these sheds ranged from $7.10 to $10.50 per square foot, with many sheds built for approximately $9.00 per square foot, which we adopt as the most-likely value (Antares Group, 2009). We assume a nominal size for a storage shed of 25,000 square feet and a storage capacity of 7,500 bales (Antares Group, 2009). Storage sheds are assumed to occupy two acres of land with a rental rate of $80 per acre; the ownership and operating costs of the storage shed are assumed to be 12 percent of the construction costs per year (Duffy, 2008).

Costs of loading and unloading are derived from custom rate surveys and standard planning factors for agricultural equipment. We assume that a diesel-powered skid loader with a power rating of 60 horsepower is used to load and unload bales from the truck. The most-recent hourly rate for a skid loader in Iowa is $51 per hour, with a range of $25 to $80 per hour (Edwards and Johanns, 2010). The specific fuel consumption of a diesel engine in this class is approximately 0.044 gallons per horsepower hour (Edwards, 2009). We assume a labor cost of $12.50 per hour and a price of diesel of $2.50 per gallon. Labor costs are increased by 15 per-

cent to account for nonproductive time on the job (Edwards, 2009). Load and unload times are 30 minutes and 20 minutes, respectively (Duffy, 2008). To estimate the cost of the nonproductive time taken to load and unload the truck, we assume a rental rate for the truck and trailer of $69 per hour (Minnesota Department of Labor and Industry, undated).

Using the parameters listed above, we can provide an estimate of the costs per ton (or costs per GJ) of transporting biomass from a farm to a storage facility, storing it for a season, and delivering it to a plant. Note that an additional load-and-unload operation is included in the costs. The following equation represents the costs of transportation and storage on a per–ton delivered basis:

$$\text{Cost}_{\text{transportation}}(d,m) = \frac{\$4.00/\text{loaded mile}}{42\ \text{bales}/\text{load}\ (m\ \text{tons/bale})_{\text{crop}}} d +$$

$$\frac{2 \times (0.5\ \text{hr load} + 0.3\ \text{hr unload})}{42\ \text{bales}/\text{load}\ (m\ \text{tons/bale})_{\text{crop}}} \times \begin{pmatrix} \$51/\text{hr loader} + \$69/\text{hr truck and trailer } + \\ 2 \times 1.15 \times \$12.50/\text{hr labor} + \\ 60\ \text{hp} \times 0.044 \text{gal/hp-hr} \times 1.15 \times \$2.50/\text{gal} \end{pmatrix} +$$

$$\frac{\$9.00/\text{ft}^2 \times 25{,}000\ \text{ft}^2 \times 0.12/\text{yr} + 2\ \text{acres} \times \$80/\text{acre}}{7{,}500\ \text{bales/yr}\ (m\ \text{tons/bale})_{\text{crop}}},$$

where d is the distance traveled and m is the mass of a bale in tons.

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