THE ECONOMIC PROSPECTS OF CELLULOSIC BIOMASS FOR BIOFUEL PRODUCTION

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ABSTRACT

THE ECONOMIC PROSPECTS OF CELLULOSIC BIOMASS
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Alternative fuels for transportation have become the focus of intense policy debate and legislative action due to volatile oil prices, an unstable political environment in many major oil producing regions, increasing global demand, dwindling reserves of low-cost oil, and concerns over global warming. A major potential source of alternative fuels is biofuels produced from cellulosic biomass, which have a number of potential benefits. Recognizing these potential advantages, the Energy Independence and Security Act of 2007 has mandated 21 billion gallons of cellulosic/advanced biofuels per year by 2022. The United States needs 220-300 million tons of cellulosic biomass per year from the major sources such as agricultural residues, forestry and mill residues, herbaceous resources, and waste materials (supported by Biomass Crop Assistance Program) to meet these biofuel targets.

My research addresses three key major questions concerning cellulosic biomass supply. The first paper analyzes cellulosic biomass availability in the United States and Canada. The estimated supply curves show that, at a price of $100 per ton, about 568 million metric tons of biomass is available in the United States, while 123 million metric tons is available in Canada. In fact, the 300 million tons of biomass required to meet EISA mandates can be supplied at a price of $50 per metric ton or lower.

The second paper evaluates the farmers’ perspective in growing new energy crops, such as switchgrass and miscanthus, in prime cropland, in pasture areas, or on marginal lands. My analysis evaluates how the farmers’ returns from energy crops compare with those from other

field crops and other agricultural land uses. The results suggest that perennial energy crops yielding at least 10 tons per acre annually will be competitive with a traditional corn-soybean rotation if crude oil prices are high(ranging from $88-$178 per barrel over 2010-2019). If crude oil prices are low, then energy crops will not be competitive with existing crops, and additional subsidy support would be required. Among the states in the eastern half of US, the states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia are found to be economically more suitable to cultivate perennial energy crops.

The third paper estimates the optimal feedstock composition of annual and perennial feedstocks from a biorefinery's perspective. The objective function of the optimization model is to minimize the cumulative costs covering harvesting, transport, storage, and GHG costs, of biomass procurement over a biorefinery's productive period of 20 years subject to various constraints on land availability, feedstock availability, processing capacity, contracting needs and storage. The results suggest that the economic tradeoff is between higher production costs for dedicated energy crops and higher collection and transport costs for agricultural residues; the delivered costs of biomass drives the results. These tradeoffs are reflected in optimal spatial planting pattern as preferred by the biorefinery: energy crops are grown in fields closer to the biorefinery and agricultural residues can be sourced from fields farther away from the biorefinery. The optimization model also provides useful insights into the price premiums paid for annual and perennial feedstocks. For the parameters used in the case study, the energy crop price premium ranges from $2 to $8 per ton for fields located within a 10 mile radius. For agricultural residues, the price premiums range from $5 to $16 per ton within a 10-20 mile radius.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

1.1 Introduction

Alternative fuels for transportation have become the focus of intense policy debate and legislative action due to volatile oil prices, an unstable political environment in many major oil producing regions, increasing global demand, dwindling reserves of low-cost oil, and concerns over global warming. A major potential source of alternative fuels is biofuels produced from cellulosic biomass, which have a number of potential benefits. First, the raw materials used in the production of cellulosic biofuels are largely waste materials from agriculture, forestry, or other non-food crops. The use of wastes overcomes the problems of using food and feed grains, such as corn, for biofuel production . Second, cellulosic biofuels help reduce greenhouse gas emissions relative to fossil fuels and other biofuels (e.g. corn ethanol). Third, the biofuels from cellulosic raw materials can be ‘drop-in fuels;’ that can be more easily integrated with the existing fuel distribution infrastructure compared to ethanol produced from corn .[1]

Recognizing these potential advantages, the Energy Independence and Security Act of 2007 has mandated 21 billion gallons of cellulosic/advanced biofuels per year by 2022 . One of the major purposes of this act is to facilitate rapid growth of cellulosic and advanced biofuels. EISA provides various support measures, such as subsidies, loan guarantees, and tax credits for biorefineries construction, technology development, and cellulosic biomass supply. Notwithstanding these support measures, the growth in cellulosic ethanol industry has rather been slow . The major limiting factors are the difficulties and uncertainties associated with reliable supply of cellulosic biomass . For a rapid development of cellulosic biofuels, it is

[1] Advanced cellulosic biofuels (butanol, and other renewable fuels) do not have the corrosive problem of ethanol.

important to create a robust supply of cellulosic biomass raw materials. In this dissertation, I focus on three specific issues pertaining to cellulosic biomass supply raw materials.

The United States needs 220-300 million tons of cellulosic biomass per year to meet EISA biofuel targets by 2022.[2] Supply of such huge quantities of cellulosic biomass is unprecedented and raises many key questions: 'What are the types, their geographic distribution, and supply costs of cellulosic biomass materials? What regional differences and advantages exist for energy crops envisioned as a major feedstock by USDA? What price and contract incentives are required to promote perennial energy crops to make them a reliable feedstock source alongside annual feedstocks? How does crude oil price uncertainty affect the development of cellulosic biomass industry? How do the differences between annual vs. perennial feedstocks affect optimal supplies of multiple feedstock to a biorefinery? And finally, what are the environmental and ecological implications of diverting biomass from their current uses?'

My research addresses three key questions among these: (i) How much cellulosic feedstock is available in the US and Canada for biofuel production and at what prices? (ii) How competitive are dedicated energy crops compared to current conventional crops after taking into account uncertainties in costs and returns, on a regional basis? (iii) What is the optimal mix of feedstocks for a given biorefinery, taking into account the differences between feedstocks in terms of material costs, temporal yield patterns, density of biomass availability, transport costs, lifecycle GHG emissions and contracting constraints? My analysis focuses on four sources of cellulosic biomass currently promoted under the Biomass Crop Assistance Program : agricultural

[2] assuming a conversion rate of 70-90 gallons per ton of cellulosic biomass

residues, forestry and mill residues, herbaceous resources, and waste materials.[3] These four biomass resources are currently available or can be cultivated to meet the biofuel production targets. Agricultural residues, forestry and logging residues, and municipal solid waste streams are readily available, are replenished annually, and generally do not have significant other uses. Perennial biomass sources, such as herbaceous energy crops (e.g., miscanthus and switchgrass), are said to have huge potential in the near term . The following paragraphs summarize the three papers and their contributions.

Paper #1: Biomass supply for biofuel production: Estimates for the United States and Canada

The first paper analyzes cellulosic biomass availability in the United States and Canada.. It estimates static supply functions for the four major cellulosic biomass feedstocks namely, agricultural residues, dedicated energy crops, municipal solid waste and forest residues. Agricultural residue quantities are estimated based on the amount of crop output from major grain crops, including corn, wheat, barley, oats, and rice. The supply costs depend on harvest and transport costs. Energy crop quantities are derived based on yield assumptions that vary by U.S. states. The quantity of energy crops available depends on how competitive these crops are in comparison to existing agricultural uses of land, while the regional production costs generate their supply costs. Three, municipal solid waste (MSW) quantities are calculated based on the organic portion that can be used for biofuel production. MSW supply costs depend on the state's landfill tipping fees and on sorting and processing costs. Four, forestry and logging residue quantities are computed based on their current uses for fiber and combustion fuel. For logging residues, the supply costs include the opportunity costs of harvesting and transporting costs; for

[3] The BCAP program provides subsidies or loan guarantees for biofuel and other bioenergy projects that use cellulosic biomass. BCAP program also supports other sources of biomass (algae or perennial tree crops) for electricity generation.

mill residues, the supply costs include their opportunity costs in existing uses (fiber, fuel or other feedstocks) and other costs of transporting them to the biofuel plant .

The estimated supply curves show that, at a price of $100 per ton, about 568 million metric tons of biomass is available in the United States, while 123 million metric tons is available in Canada. In fact, the 300 million tons of biomass required to meet EISA mandates can be supplied at a price of $50 per metric ton or lower. At this price, the mix of feedstocks would comprise mainly of agricultural residues and forest/ mill residues. The quantities of municipal solid wastes are expected to be meager. Small quantities of energy crops will be produced only in some southern U.S. states. The estimates of agricultural residue supply are very sensitive to the assumed fraction of residues that can be sustainably removed from the field; the potential of municipal solid waste as a feedstock is also found to depend on which components can be economically converted into liquid biofuels. The results show that most of the cellulosic biomass required in meeting the current biofuel mandates can be supplied without huge changes in land use.

Paper #2: Regional competitiveness of energy crops

The second paper evaluates the farmers' perspective in growing new energy crops, such as switchgrass and miscanthus, in prime cropland, in pasture areas, or on marginal lands. Switchgrass and miscanthus are two energy crops widely studied across the United States. Switchgrass test plots exist in the states of Tennessee, Oklahoma, Maryland, Iowa, Nebraska, and the Dakotas , while miscanthus is promoted in Illinois and a few other Midwestern states . My analysis evaluates how the farmers' returns from energy crops compare with those from other field crops and other agricultural land uses. In particular, it studies whether diverting the lands to energy crop production would increase or decrease expected farmers' net returns over a

10 year period. The objective is to identify states in the eastern half of the United States where the economic returns from energy crops are greater than or equal to the returns from existing agricultural land uses. The economic returns from energy crops depend on crude oil prices because they affect the prices for cellulosic biofuels and the derived demand for cellulosic raw materials (energy crops, in this case), as well as costs of energy crop production. The fluctuations in crude oil prices, at yearly intervals, are modeled to capture the impact of crude oil price changes over the next 10 years. The simulated crude oil prices are used to derive empirical probability distributions for the Net Present Values (NPV) of returns from energy crops and other land uses. Similarly, I use Monte Carlo simulations to model the empirical distributions in crop yields, output prices, and agricultural input prices for 2010-2019. Long run cointegration relationships between crude oil prices and agricultural output and input prices drive the simulation. Probability distributions of regional temperature and precipitation values in the long run are employed to simulate energy crop yield distributions These simulated distributions of returns are used to evaluate the competitiveness of energy crops. Specifically, the probability of receiving higher returns from energy crops (compared to field crops) is estimated..

When the farmers are risk averse, they do not consider only the expected economic returns (NPV) of energy crops, but also the risk around the expected returns. I estimate the state level average farmer risk aversion coefficients using the stochastic power function approach. The risk adjusted competiveness of energy crops is determined by comparing the certainty equivalent NPVs of returns.

The results suggest that perennial energy crops yielding at least 10 tons per acre annually will be competitive with a traditional corn-soybean rotation if crude oil prices are high(ranging from $88-$178 per barrel over 2010-2019). If crude oil prices are low, then energy crops will not be competitive with existing crops, and additional subsidy support would be required. Among the states in the eastern half of US, the states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia are found to be economically more suitable to cultivate perennial energy crops.

Farmers in the above states may prefer to adopt energy crops because these crops have a low dependence on crude oil inputs. Hence, their risk-averse nature might drive them to adopt more energy crops when crude oil prices climb and stay consistently higher. A key feature of the results is that the economic returns from major field crops such as corn, soybeans, and wheat are sensitive to higher crude oil prices. Their returns decrease much more than the returns for energy crops. This increases the probability of receiving higher NPV from energy crops, making it an attractive crop alternative. Biomass Crop Assistance Program (BCAP) provides subsidies for cellulosic biomass. The BCAP subsidy matches the cellulosic biomass market prices dollar-for-dollar, up to a maximum of $45 per ton. Such matching subsidies effectively result in higher subsidy payment when crude oil prices are high, even though there is less of a need for biomass subsidies. The results from my study depict a clear need for counter cyclical biomass subsidies tied to crude oil prices instead of the current practice of matching biomass prices.[4]

Paper #3: Choice of optimum feedstock portfolio for a cellulosic ethanol plant – A multi-period linear programming solution

The third paper estimates the optimal feedstock composition of annual and perennial feedstocks from a biorefinery's perspective. In identifying the optimal feedstock composition, the model considers several objectives: (i) ensuring reliable supply of biomass over the entire productive lifetime of the cellulosic biorefinery, (ii) minimizing procurement costs (including

[4] When crude oil prices are low, the cellulosic biofuel prices are low as well, resulting in lower subsidies.

harvest, baling, transport, storage, and seasonal costs), and (iii) maximizing the reduction in greenhouse gas (GHG) emissions

The objective function of the optimization model is to minimize the cumulative costs covering harvesting, transport, storage, and GHG costs, of biomass procurement over a biorefinery's productive period of 20 years subject to various constraints on land availability, feedstock availability, processing capacity, contracting needs and storage. The model makes several important contributions. First, existing studies treat the available biomass quantities in the region as exogenously given and then try to minimize procurement costs. In comparison, my proposed model treats biomass acreage to be harvested as an endogenous decision variable subject to overall biomass availability constraints.[5] In addition, transport costs, seasonal costs, and environmental costs are also endogenously determined as a function of harvesting decisions in my model. Second, my model explicitly considers changes in yield patterns that occur over a perennial energy crop's lifetime and the corresponding impacts on optimal feedstock mix. In contrast, most other studies assume that average yields and feedstock mix remain constant over a biorefinery's lifetime. Third, my model also explicitly incorporates the flexibility with respect to agricultural residue harvesting, and the necessity to enter into longer term contracts with energy crop producers that assure harvesting each year, and the resulting cumulative effects on the feedstock mix. This is accomplished by forcing the model to harvest all energy crop biomass produced over its 10 year productive period; the lack of this restriction on agricultural residue harvest is referred to as flexibility in biomass harvest in this model. Fourth and finally, the

[5] Mapemba et al (2008) also model area harvested as an endogenous variable in an optimization model. However, their analysis is specific to one region in Oklahoma. My model extends their analysis by modeling a general harvest-shed area, with multiple concentric circles around the biorefinery, which could be applied to any location.

impacts of GHG emissions on feedstock sourcing decisions are also evaluated. Thus, for these reasons, my model provides better insights into the realities of biomass procurement.

The model is used to calculate the optimal feedstock mix for the proposed *Abengoa Biofuels* biorefinery in Hugoton, Kansas, which is likely to use both agricultural residues and dedicated energy crops for cellulosic biofuel production. Accordingly, the parameters of the optimization model were calibrated for Hugoton, Kansas location, considering one annual feedstock (corn stover) and one perennial feedstock (miscanthus). Average biomass raw material costs are estimated at 60-70 cents per gallon of annual cellulosic biofuel production for this biorefinery. At the optimum, up to two-thirds of the plant's cellulosic biomass would come from dedicated energy crops. Though more costly to produce, dedicated energy crops are preferred due to their higher per-acre yields and wider harvest windows. Alternative harvesting scenarios suggest that feedstocks that widen harvest windows or feedstocks that have higher biomass yield densities will feature prominently in the optimal biomass feedstock portfolio.

The economic tradeoff is between higher production costs for dedicated energy crops and higher collection and transport costs for agricultural residues. The delivered costs of biomass (which is reduced as part of the cost minimization problem) drives the results. The ideal way to reduce costs would be to generate higher biomass yields and incur lower transportation costs – the feedstock that satisfies both these requirements would be 'energy crops grown closer to the biorefinery.' The energy crops can offset their higher costs of production only when located closely to the biorefinery thereby reducing the transport costs. The differences in transport costs from different locations is a crucial determinant of optimal cropping pattern. To offset the higher transport costs, agricultural residues characterized by lower production costs would be preferred.

These tradeoffs are reflected in optimal spatial planting pattern as preferred by the biorefinery: energy crops are grown in fields closer to the biorefinery and agricultural residues can be sourced from fields farther away from the biorefinery. The optimization model also provides useful insights into the price premiums paid for annual and perennial feedstocks. For the parameters used in the case study, the energy crop price premium ranges from $2 to $8 per ton for fields located within a 10 mile radius. For agricultural residues, the price premiums range from $5 to $16 per ton within a 10-20 mile radius. Over time, the premiums declined for agricultural residues and rose for energy crops. In any given time period, the price premiums increased with proximity to the biorefinery. The results suggest that optimal spatial planting pattern depend on economic factors (harvesting, and transporting costs) which in turn depend on the temporal patterns of biomass feedstock yields, their respective yield density (tons per acre) and area available for sourcing cellulosic feedstocks within the harvest shed.

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BIOMASS SUPPLY FOR BIOFUEL PRODUCTION: ESTIMATES FOR THE UNITED STATES AND CANADA[1]

2.1 Introduction

Alternative fuels, especially biofuels for transportation have become the focus of intense policy debate and legislative action due to volatile oil prices, unstable political/military environment in major oil production regions, rapidly increasing global demand and dwindling reserves of oil, and concerns over global warming. Promoting biofuel production is also viewed as means to reduce high agricultural program costs and to promote rural incomes in North America. While ethanol from grains is expected to account for most of the US/Canada biofuel production in the short run, ethanol from lignocellulosic biomass is considered to be more attractive from a long term sustainability perspective because of significantly lower life cycle greenhouse gas emissions compared to grain ethanol, widespread domestic feedstock availability, and the potential to ameliorate the conflict over food v/s fuel use of grains . Reflecting this view, the renewable fuel standards under the US Energy Independence and Security Act of 2007 (EISA) set forth a phase-in for renewable fuel volumes beginning with 9 billion US gallons (34 billion liters) in 2008 and growing to 36 billion gallons or 136 billion liters by 2022 . The conventional starch-based biofuel volumes are limited to 15 billion gallons and advanced biofuel volumes are mandated to be 21 billion gallons including 16 billion gallons of cellulosic ethanol by year 2022. However, achieving the cellulosic ethanol mandate critically depends on the availability of biomass in sufficient quantities at reasonable costs for conversion to liquid fuels.

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[1] published in *BioResources* Journal 4(3): 1070-1087 (with Dr. Satish Joshi and Dr. Heather L. MacLean)

Cellulosic feedstocks include agricultural residues, forest and mill residues, organic/lignocellulosic portion of municipal solid waste, and energy crops grown purposely for conversion to fuels. Over the last decade, a number of studies, assessing biomass potential at various regional, national and global scales have been published. While few studies include all major feedstocks , many focus on a single feedstock, such as agricultural residue assessments , and , and energy crop assessments . Comprehensive biomass feedstock assessments at the national level have been completed for the US and Canada . However, as conclude from their review of 17 studies of biomass energy supply, the studies vary considerably in their assumptions, models and methodologies employed, feedstocks covered, temporal and spatial scales, production technology projections, and policy scenarios.

Four general approaches have been taken in estimating biomass supply potential in these studies: (1) inventories of potential biomass sources with minimal attention to the economics of actual supply and prices at which these quantities will be available; (2) static supply curves which estimate quantities of biomass supplied at various exogenously determined prices assuming everything else remains constant; (3) projections of supply quantities in competition with other crops and uses, but under current productivity and policy conditions; and (4) dynamic projections of supply quantities in competition with other crops and uses, under projected/potential productivity and policy conditions, ethanol/gas prices and quantity mandates. In addition, some studies use a bottom-up approach where biomass potentials are assessed at local/regional level, which are then aggregated into national level estimates, while some other studies directly estimate national potentials based on national economic models.

Published studies have used a mixture of these approaches and often within a single study, and the details of all the model and parameter assumptions are often not explicitly reported. As a result, estimates of bioenergy potential vary significantly across studies, and comparison and reconciliation of differences becomes difficult. A recent review of fifteen North American studies, carried out by , also finds large variations in estimated potential biomass supply across those studies for these reasons.

In this study, supply quantities for various biomass feedstocks in the US and Canada are estimated using a bottom-up, static supply function approach. The relatively simple, but consistent approach will provide more realistic estimates of short term supply of biomass feedstocks. Such short-run estimates will be useful for assessing feasibility of proposed cellulosic ethanol facilities. While similar supply functions have been previously estimated for specific feedstocks or regions, a major contribution of this study is providing comprehensive estimates for both US and Canada, covering all major feedstocks.

2.2 Methods

Estimates of biomass supply from, agricultural residues, forest and mill residues, cellulosic portions of municipal solid waste (MSW) and energy crops were developed. The methods used for each feedstock are summarized below.

Agricultural Residues

For estimating supply of agricultural residues a procedure similar to Gallagher et al (2003) was followed. Agricultural residue supply functions were estimated at the individual county level for the US and at the census subdivision level for Canada. These supply functions were then aggregated to estimate national level supply functions. The steps in the estimation procedure are as follows.

The average crop output data for the years 2000-2002 was used to estimate the total quantity of residue generated employing average residue factors i.e., residue generated per ton of crop output. Assumed residue factors were 1.5, 1, 1 and 1.27 for barley, corn, rice and wheat respectively. Four major crops: corn, wheat, rice and barley are considered for the US estimates. The crop output data are from National Agricultural Statistics Service . How much of this total quantity of residue generated will be supplied to the market for conversion is a decision made by the farmers, which is governed by: regulatory restrictions on residue removal and soil cover to prevent soil erosion, residue harvesting, storage and transportation costs, opportunity cost of soil fertilization from leftover residues, animal feed value of the residue, and other opportunity costs. The residue that needs to be left on the field to prevent soil erosion depends on local topographic, soil and wind conditions. It was assumed that recommended amounts of crop residues, that keep the soil erosion below the threshold levels, are left on the field as soil cover. Gallagher et al (2003) estimate that for corn, 0.65 tons (t) per acre of chopped corn stover left in the fall fulfills soil erosion prevention requirements. Similarly for wheat and other small grains 0.32 t/acre of fall residues satisfy the requirement including the loss of residues during the winter . For winter wheat fallow, the winter loss occurs twice, so the minimum fall residue would be 0.46 t/acre . An average of these two estimates (0.39 t/acre) was used for wheat, barley and rice.

Next, the assumption was that if the price offered by ethanol conversion facilities is lower than the feed value of the residues, farmers will first sell the residues as cattle-feed until the local forage demand is met; however, at prices higher than the feed value, this additional quantity of residues will be supplied for conversion to ethanol. The estimates for the feed values are updated from Gallagher et al. (2003) and range from $28.70/t (for wheat) to $56.74/t (for corn) in 2008 dollars. The forage demand was estimated based on county livestock population and hay crop production using the relation: Forage demand = County Cattle Population * Daily Feed Requirements * (365 – Pasture feeding season length) – local hay production.

Excess residues after meeting soil conservation needs and the local animal feed requirements will be available for conversion to ethanol only if the price offered is high enough to compensate for the costs incurred for harvesting, storage and transporting the residues. Further, residues left on the field have some fertilizer value, which subsequently reduces fertilizer requirements for the next season. The price offered should also cover this lost fertilizer value. The harvesting and transportation costs and lost fertilizer values for different residues were estimated and it was assumed that farmers will supply remaining residues at a price equal to the sum of these costs. The main operations in harvesting include chopping, baling and hauling. The estimated chopping, baling and hauling (within the farm) expenses were $25 per acre on an average. The fertilizer nutrient value of barley straw, corn stover, rice straw and wheat straw were estimated at $14.20, $12.30, $10.30 and $9.50 per metric ton respectively .

The farm to factory gate transportation costs depend on the average transportation distance, which in turn depends on the density of crop residues and the size of the conversion plant. For a plant with an annual capacity of Q (in metric tons) of residues, the radius of the collection area (assuming a circular one) is $(Q/\pi d)^{0.5}$, where d is the density of residue availability in t/square mile. The average distance of collection is $0.67(Q/\pi d)^{0.5}$. The county residue density *d* was calculated by dividing the total quantity of residue available after meeting soil conservation and cattle feed requirements, by the total land area of the county. Harvesting and transportation costs were calculated by using weighted average costs of different crops, where the proportion of the different crop residue available after meeting soil conservation requirement was used as a weighting factor. It was also assumed that the ethanol conversion plant had a processing capacity of 2000 metric tons per day (tpd) of residues and average transport costs were $0.40/ton mile in estimating transportation costs.

Similar procedures were employed to estimate agricultural residue supply functions for Canada. However, because Canada does not produce any rice, oats was considered instead of rice. A dataset at the Census Sub Division (CSD) level for Canada, similar to the county level dataset for the US was developed. Data on crop area harvested and cattle population were collected from 'Statistics Canada' publications. Average crop yield data (barley, corn, oats and wheat) for the years 1999-2003 are from Statistics Canada reports . The data is reported at the CSD level. Other parameters such as residue factors, feed value, fertilizer value, length of foraging season etc. were assumed to be similar to those for the US. Because data on crop yields at the CSD level were not available, the average yield and residue density at the Canadian provincial level were assumed to be the same for all CSD within that province. The individual county/CSD supply functions were then aggregated to derive national level agricultural residues supply function for Canada.

Forest Residues

Forest residues comprise of logging residues that are generated during the harvesting operations, and mill residues that are generated in saw mills, paper mills and other wood processing units. Logging residues are currently left at harvesting sites and hence need to be collected and transported from the forests, while mill residues are available at processing facilities and currently being used either as fuel or as raw material for other wood products.

reports the total quantities of logging residues and mill residues produced in various states of the US, which are based on the USDA Forest Service's Timber Product Output database for 2002. Logging residue quantities for Canada were computed from the total roundwood production reported at provincial level in Canadian national forestry database for the year 2006 . For Canada, it was assumed that logging residue production would be16% of the total roundwood production (Mabee, 2006). In comparison, logging residue estimates for the US, vary between 4% and 28% of total roundwood production . Data on the quantity of Canadian mill residues were drawn from .

It was assumed that all the logging residues produced in a US state or Canadian province would be available at a price equal to the sum of grinding costs and transportation costs. Mill residues were assumed to be available for conversion if the price offered was greater than the opportunity cost of their current use as fiber, fuel or other feedstocks. The US state level estimates of mill residues used as fiber, fuel and other applications were from . The opportunity costs for the various types of residues were estimated based on their current use: the mill residues used for fiber products (pulpwood) were valued at $36/dry ton (dt), the fuel use was valued at $23.65/dt (i.e.

$1.25/million BTU based on coal price) and all other uses were valued at $16/dt. The remaining residues that are not currently used were assumed to be available for free . It was assumed that logging residues were uniformly distributed in the timberland area of the region being considered and the average transport distance required to supply a 2000 tpd ethanol plant was calculated using similar methods as outlined above for agricultural residues. The logging residues from the forests were valued at their fuel use value ($23.65/dt) which would be their opportunity costs in heat and power production. The estimated average distance for collection of forest logging residues varied between 19 to 55 miles based on the state geographic area and density of forest residues. These distance estimates were combined with the transportation cost of $0.40 per ton-mile as in the previous case to compute the transportation costs. Since mill residues were readily available at the processing facilities (like paper and pulp mills) a transport cost of $5/t was assumed for mill residues. The estimated state/province level supply functions were then aggregated to estimate the national supply functions.

Municipal Solid Wastes

The USEPA and the *BioCycle* magazine annually estimate the total quantities of municipal solid waste (MSW) generated, recovered and discarded in the US. The USEPA estimates are at an aggregate national level based on material flow analysis, while the *Biocycle* estimates are based on an annual survey of state level MSW officials. In Canada, Statistics Canada publishes biannual data on waste disposal and diversion at the provincial level. We use state level estimates of MSW generated from the 15^{th} annual survey conducted by the BioCycle magazine and Earth Engineering Center of Columbia University . It was assumed that 66% of the wastes were organic materials suitable for cellulosic ethanol production, based on estimates from USEPA . An average moisture content of 40% was assumed in deriving dry biomass equivalent of MSW feedstock, based on estimated moisture content of various constituents in MSW which can vary from 2 to 70% .

Since a well-established collection system for MSW is currently operating, and tipping fees are paid to dispose MSW, all the lignocellulosic portion of MSW is essentially available (albeit at the landfill) at a negative price equivalent to the current landfill tipping fee. The tipping fees in 2006 ranged from $21/t to $123/t in the US and from $40/t to $75/t in Canada . The total quantity of MSW currently landfilled in a state/province was assumed to be available at a negative price equivalent to the average tipping fee for the particular US state or Canadian province. Because the cellulosic portion of MSW needs to be separated from other constituents before conversion to ethanol, estimated separation/sorting and transportation costs of $55/wet ton was added to the negative price to estimate the ethanol feedstock supply price. The processing cost estimate is based on an update of a previous estimate . The state (province) level quantity and price data were then combined to estimate the total quantity of MSW feedstock supplied at various prices at national level.

Energy Crops

The potential supply of energy crops when they are competing with conventional crops is a complex function of several factors. Farmers will switch to energy crops only if expected returns from the energy crops are higher than returns from growing conventional crops and/or keeping the land idle under conservation programs such as the US Conservation Reserve Program (CRP) and collecting rental payments as well as the government support payments. In addition to switching to energy crops, farmers will also be switching between conventional crops based on relative expected returns. These returns are governed by expected prices for different crops, yield and production cost structure for energy crops compared to that of conventional crops. These costs and yields also differ by the geographical location. Hence, the estimation of potential supply of energy crops has to be carried out using an integrated model of agriculture that incorporates the inter-dependencies across individual commodity grain, livestock, dairy, consumption and international sectors, as well as agricultural policy variables. Most of the current projections of energy crop supply in the US, are derived from an integrated comprehensive model of US agriculture, POLYSYS, developed and maintained by the Agricultural Policy Analysis Center (APAC), University of Tennessee, Knoxville . In fact, most of the estimates of bioenergy crop supply published by the US Department of Energy (USDOE) and US Department of Agriculture (USDA) draw on the POLYSYS model estimates. For example, see Perlack et al. (2005) and De La Torre Ugarte et al. (2000, 2003). However, estimates of energy crop supply using the POLYSYS model vary significantly depending on variations in the underlying production/supply constraints, and assumptions about energy crop productivity, relative profitability and policy variables.

To derive static supply curves for energy crops that were consistent with other biomass feedstock estimates, a relatively simple approach was used. It was assumed that farmers will potentially divert land from current traditional crops to energy crops (e.g. switchgrass) if the 'returns over variable costs' (ROVC) for switchgrass were more than the returns over variable costs for the traditional crops. Since the current ROVC were adequate enough to cover the fixed costs such as land value and opportunity costs of labor and overhead charges, and retain the land under production, a higher ROVC from energy crop production would make switching to energy crops attractive.

Using county level crop production data from USDA - ERS, gross revenues per acre for various crops namely – corn, soybeans, wheat, rice, barley, oats, and cotton at the county level, were calculated using state average commodity prices and variable costs of production . The variable costs of production included the costs of seeds, fertilizers, pesticides, energy for machinery operations and custom work. The returns over variable costs (ROVC – which is an estimate of fixed costs of agricultural production that are being covered currently) were calculated by subtracting these variable costs from total revenues. Average ROVC for the period 2002-05 for all major crops in each US County along with harvested acreages were computed. Government payments were not included in ROVC estimates because these payments have been effectively decoupled from commodity production since the passage of Farm Bill 2002 .

Next ROVC for growing switchgrass at various switchgrass prices were estimated at the county level. Counties in the eastern half of the US including the Dakotas, Oklahoma and Texas, where switchgrass can be grown under rain-fed conditions were considered. To account for differences in state level yields and costs of production, the states were divided into three regions: south, central and north. In the southern region (AL, AR, FL, GA, KY, LA, MS, NC, OK, SC, TN, TX, VA, WV) the energy crop yield was assumed to be higher at 8 dt/acre at an average variable cost of $259.56 per acre . In the central states (IL, IN, IA, KS, MO, NE, NY, OH, PA) the yield was assumed to be 4.45 dt/acre at an average variable cost of $211.71/acre . The northern states (CT, DE, ME, MD, MA, MI, MN, NJ, RI, SD,VT, WI) are located in much colder climates and the yields were found to average only 2.79 dt/ acre with variable costs of $128.32 per acre . The variable costs include seed costs, initial establishment costs, fertilizer costs, harvesting costs and baling costs. It was assumed that once established, switchgrass can be harvested over a period of 10 years. These yield and production costs are based on realized values, however improvements in switchgrass yields are likely in the future. Although other energy crops such as miscanthus and energy cane have been considered potentially attractive, the analysis is limited to switchgrass, to be consistent with previous analyses .

The average annual ROVC of field crops were compared with ROVC from switchgrass at various switchgrass prices and it was assumed that 10% the land currently earning lower ROVC than that of switchgrass would be converted to energy crop production.[2] A variety of factors affect the crop-switching decision including subsequent changes in relative crop prices and returns as a result of crop switching, land characteristics, local weather/rainfall conditions, expectations, farmer expertise and risk preferences. 10% land conversion was used as an indicative aggregate constraint resulting from all these considerations. The estimates using this simplification are consistent with the earlier work using POLYSYS models that estimated 5 to 14 per cent of crop land being converted into energy crops . Transportation costs from the farm to factory gate were estimated employing a similar approach as for agricultural residues.

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[2] To illustrate, Baldwin County (FIPS code 1003) in Alabama had an average of 4,250 acres under corn, 10,167 acres under soybeans and 7,933 acres under wheat crop during 2002-05. The net returns over variable costs for those crops during those years were $140, $109 and $61 per acre respectively. If the energy crops were able to generate a return of $50 per acre, then none of the land under these crops would be diverted to energy crops. But if the ROVC from energy crops were $125 per acre, then we assume that 10% the soybeans and wheat acreage will be converted to energy crops as the latter is more profitable.

Canadian energy crop supply

The Whole Farm Database managed by Statistics Canada reports harvested acres and total revenues for various crops at the Census Agricultural Region level (table series C) in Canada . However the expenditure data are not available separately by individual crops but aggregate expenditure per acre for the portfolio of crops is available. Hence the average farm ROVC (dollars per acre) from the existing 'portfolio' of crops was compared with the potential returns from energy crops. The Canadian crop portfolios included the major crops such as wheat, oats, barley, rapeseed, soybeans, corn, small grains and forage crops. The land area switching to energy crops at various energy crop prices was estimated using similar procedures outlined above for the US energy crops.

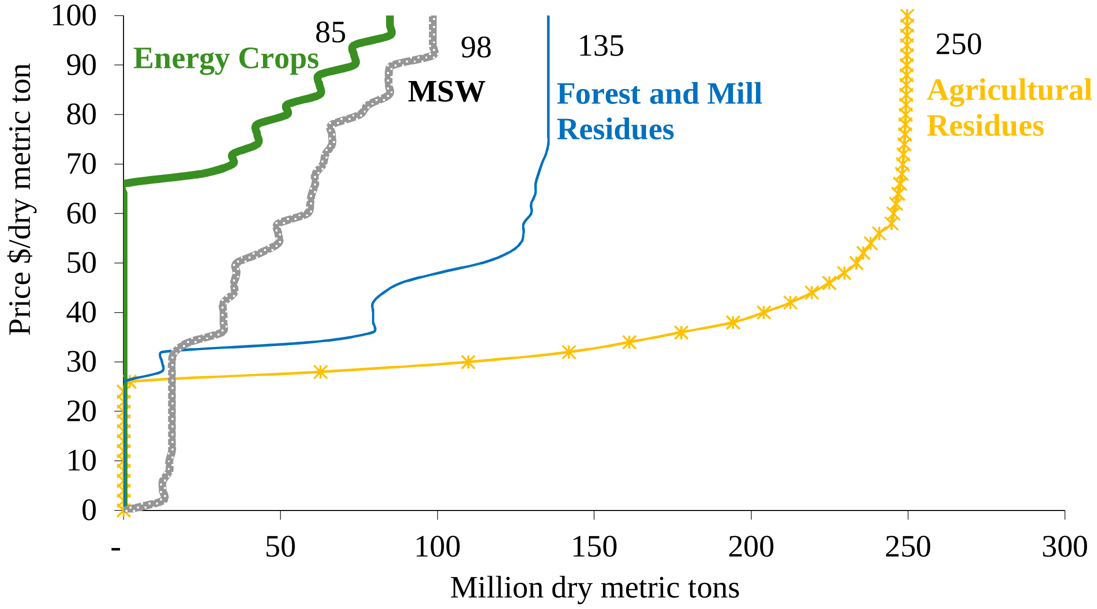
2.3 Results

US Biomass Supply

Figure 2.1 and Table 2.1 summarize the biomass supply estimates for the US. The supply curves are shown only up to the price level of $100 per dry metric ton (dt), beyond which biomass use for ethanol conversion will likely be uncompetitive. The total biomass potentially available in the US, at a price of $100/dt is 568 million dt, comprising of about 250 million dt (44% of total supply) of agricultural residues, and 135 million dt (24%) of forest and mill residues. Under the assumption of planting a maximum of 10 per cent of crop land in the eastern half of US, energy crops such as switchgrass and miscanthus would approximately yield 107 million dt of biomass; of which about 85 million dt will be available at a price of $100/dt.

From Table 2.1, it can be seen that 384 million dt of this biomass will be available at price of $50 /dt in the US – primarily from agricultural residues and forest feedstocks. Compared to that the minimum price at which switchgrass starts becoming available is $67/dt. The reasons for higher prices for energy crops are two-fold: (i) the field crops that are displaced by energy crops generate higher returns raising the break even prices of energy crops and (ii) the yield of energy crops is currently low in temperate climates. In fact, some studies consider energy crops as future (third generation) biomass feedstock after corn grains and agricultural/forest residues . A total of 98 million dt of MSW is potentially available for cellulosic ethanol production, however only less than a third of MSW will be available at price of $50/dt, due to higher MSW processing costs.

Figure 2.1: Biomass supply curves for the US[@]



[@] For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis (or dissertation).

Table 2.1: Biomass Supply Estimates for the US

Price at biorefinery gate ($/dt) [a]	Quantity supplied million dry metric tons				
	MSW	Agricultural-residue	Forest and Mill residues	Energy crops	Total*
30	15	110	12		137
40	32	204	80		315
50	36	234	114		384
60	58	245	130		434
70	63	248	133	35	480
80	75	249	135	52	512
90	86	250	135	73	544
100	98	250	135	85	568

[a] in 2008 US dollars

* Total quantities are different from the summed up values due to rounding

Canadian Biomass Supply

The potential total biomass supply in Canada is 123 million dt, with agricultural residues (42 million dt) and forest/mill residues (43 million dt) constituting 60 per cent of supply. As shown in table 2.2, the biomass in Canada is likely to be more expensive than in the US. At a price of $50/dt, only one-fourth of all potential biomass would become available in Canada, compared with nearly two-thirds in the US. The reasons are three fold: (i) the lower agricultural cropping density in Canada (due to cooler climate) leads to higher transportation costs; (ii) the yield of biomass is lower due to temperate climate and (iii) the lower population resulting in lower MSW generation. Unlike in the US, agricultural residues are more expensive than forestry feedstocks in Canada; the main reason being increased transportation costs due to lower cropping density. MSW and energy crops are costlier in the Canadian case as well. Energy crop supplies are 31 million dt at $100/dt. However, if switching to energy crops occurs in 20% of all agricultural land with lower ROVC than switchgrass, then energy crop supply can nearly double to 61 million dt in Canada.

Figure 2.2: Biomass supply curves for Canada

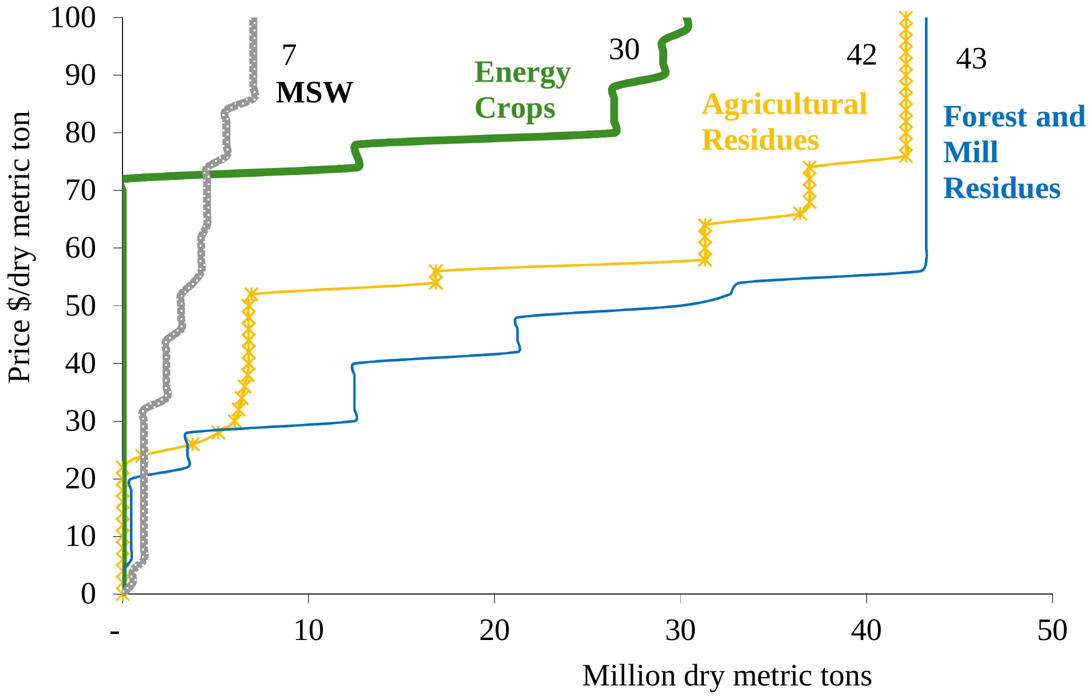


Table 2.2: Biomass Supply Estimates for Canada

Biomass Price $/dt*	Quantity Available (million dry metric tons)				
	MSW	Agricultural residue	Forest and Mill residues	Energy crops	Total**
30	1	6	12		20
40	2	7	12		22
50	3	7	30		40
60	4	31	43		79
70	5	37	43		85
80	6	42	43	26	117
90	7	42	43	30	121
100	7	42	43	31	123

* At biorefinery gate in 2008 US dollars

** Total quantities are different from the summed up values due to rounding

The renewable fuel standard provisions under the US Energy Independence and Security Act, 2007 mandate using 21 billion gallons of advanced biofuels for transportation by the year 2022, including 16 billion gallons of cellulosic ethanol . At a conversion rate of 70-100 gallons/dt the biomass requirement to supply 21 billion gallons is 210-300 million dt. These results suggest that this quantity of biomass (required by 2022) is readily available under current conditions at prices below $50/dt. Table 2.3 presents the amount of biomass required to produce 7, 14 and 21 billion gallons of cellulosic ethanol and estimated composition of biomass supplied to meet these requirements. Almost all (97%) of biomass required for meeting the advanced biofuel provisions of EISA 2007 is likely to be various types of residues, with agricultural residues accounting for 61%, followed by forest and mill residues (27%). Dedicated energy crops are likely to be a minor source.

Table 2.3: Biomass Feedstock Requirements and Expected Composition to meet Cellulosic Ethanol Production Targets in the US

Ethanol production target billion gal (at 70 gal/dt)	7	14	21
Required biomass (million dt)	100	200	300
Agricultural Residues	67.3	147.0	180.0
Energy crops	-	-	9.0
Forest and Mill Residues	12.0	22.0	80.0
MSW	20.7	31.0	31.0

Geographical Distribution

Table 2.4 shows the geographical distribution of feedstocks required to meet EISA 2007 mandates. The corn-belt states that supply agricultural residues account for the largest quantities of biomass for biofuel production, followed by states like Texas, Georgia and Oregon supplying significant quantities of forest and mill residues. It should however be noted that the states near the bottom of Table 2.4, are unlikely to have cellulosic ethanol plants due to low quantities of biomass available which would not be adequate to exploit the significant economies of scale observed in biorefineries. Mill residues account for almost all of the 80 million dt of forest and mill residues supplied. Collecting logging residues was found to be uneconomical at prices below $50/dt. Energy crops are competitive with field crops in south-eastern states, Carolinas, Tennessee, Texas and Oklahoma at prices around $50/dt.

Table 2.5 presents the geographical distribution of biomass supply at a price of $100/dt in Canada. Agricultural provinces of Saskatchewan, Alberta and Ontario account for most of agricultural residues and energy crops, while forest and mill residues account for most supplies in British Columbia and Quebec. Compared to US, a larger proportion

Table 2.4: Geographical Composition of Feedstock Mix to meet EISA Mandates
(Biomass Quantity Target: 300 million dt)

State	Agricultural Residues	Energy Crops	Forest and Mill Residues	MSW	Total
Illinois	34.79	-	0.33	5.91	41.02
Iowa	38.27	-	0.16	-	38.43
Minnesota	18.95	-	1.04	0.84	20.83
Nebraska	20.09	-	0.07	-	20.16
Indiana	16.06	-	0.65	-	16.71
Michigan	4.34	-	1.40	4.51	10.25
Washington	2.31	-	5.68	1.94	9.93
Ohio	8.70	-	0.91	-	9.61
Texas	3.21	3.36	2.23	-	8.80
Georgia	0.09	0.66	7.33	-	8.08
Oregon	0.06	-	6.54	0.87	7.47
Wisconsin	5.47	-	1.69	-	7.16
Florida	-	0.09	2.03	4.57	6.69
Idaho	2.18	-	4.42	-	6.60
Alabama	0.01	0.66	5.91	-	6.59
South Dakota	5.92	-	0.15	-	6.07
California	0.92	-	5.02	-	5.94
Missouri	4.63	-	1.11	-	5.73
Pennsylvania	0.08	-	1.49	3.52	5.08
North Carolina	0.18	0.85	4.02	-	5.04
Mississippi	0.39	0.07	4.58	-	5.04
Virginia	0.24	0.17	2.21	2.06	4.68
Louisiana	0.80	0.09	3.61	-	4.50
Kentucky	2.40	0.58	1.49	-	4.46
Arkansas	0.31	-	3.66	-	3.96
Kansas	3.25	-	0.05	-	3.30
Tennessee	0.83	0.58	1.63	-	3.04
South Carolina	-	0.51	2.51	-	3.02
Oklahoma	0.86	1.09	0.66	-	2.60
Montana	0.46	-	1.95	-	2.41
Maryland	0.65	-	0.17	1.36	2.18
New Jersey	-	-	0.08	1.98	2.06
West Virginia	-	0.46	0.82	0.58	1.86
Colorado	1.37	-	0.22	-	1.60
New Hampshire	-	-	0.94	0.39	1.33
New York	0.07	-	1.18	-	1.25
Massachusetts	-	-	0.17	0.98	1.14
North Dakota	1.01	-	0.01	-	1.01
Delaware	0.46	-	0.02	0.35	0.83

Table 2.4 (continued)					
State	Agricultural Residues	Energy Crops	Forest and Mill Residues	MSW	Total
Maine	-	-	0.44	0.36	0.79
Other States	0.13	-	0.96	0.78	1.88
US Total*	**180.00**	**9.00**	**80.00**	**31.00**	**300.00**

* Sum of state biomass supply may not equal US totals due to rounding

Table 2.5: Canada Geographic Distribution

	MSW	Agricultural residues	Forest residues	Mill residues	Energy crops
Saskatchewan	0.27	16.68	0.54	0.52	16.82
Alberta	0.86	13.27	2.73	2.63	7.17
British Columbia	0.67	-	8.70	8.40	0.14
Ontario	2.46	5.54	2.91	2.81	1.53
Manitoba	0.35	6.17	0.24	0.23	4.52
Quebec	2.06	-	4.55	4.40	0.14
Other Provinces	0.32	0.16	2.32	2.24	0.01
Canada Total*	**7.00**	**41.81**	**21.99**	**21.23**	**30.33**

* Sum of state biomass supply do not equal US totals due to rounding error

of crop land is expected to convert to switchgrass production on account of relatively lower profits from traditional row crop production Canada.

Comparison with Recent Estimates

Walsh (2008) estimates that a total of 283 million dry short tons (256 million dt) of biomass will be available at a price of $100/dry short ton ($110/dt) in 2010, consisting of 101 million dt of agricultural residues, 18 million dt of urban wastes, 54 million dt of forest residues, and 52 million dt of mill residues and 31 million dt of switchgrass. These estimates are substantially lower than our estimates. The reasons for the differences are discussed below. Since comparable studies of Canadian biomass supply curves were not available, this comparative analysis is limited to the US.

Walsh estimates that 101 million dt of agricultural residues will be available by 2010 at a price of $110/dt compared to our estimate of 250 million dt. The difference arises mainly from assumed percentage of available residues that are collected for ethanol conversion. Our analysis assumes the recommended level of residues to reduce soil erosion below tolerable levels, will be left on the field, which results in collection rate of 76% of available residues. In comparison, estimates by Walsh (2008) implicitly assume a collection of only 33-45% of available residues. Walsh estimates the amounts of residues that should be left on the field to maintain soil carbon and organic matter levels in addition to soil erosion control. Our estimates only include mandatory soil erosion control requirements, but incorporate opportunity costs of soil fertility maintenance. What is the sustainable residue removal rate is a subject of debate . Our estimates are consistent with the 'Billion ton' study by Perlack et al (2005) which assumes removal of 70-80% of residues from the fields. If the collection is limited to about 40% of available residues, our estimates are similar to those by Walsh (2008). Moreover, Walsh's estimates consider only corn-stover and wheat straw while our estimates include residues from other crops namely rice, barley and oats.

For estimating urban wastes, Walsh only considers wood portions of urban wastes; but, in this study all organic components of MSW including paper, wood, yard trimmings and food waste are included as potential feedstocks for ethanol conversion. Paper and food wastes accounted for 32.7% and 12.5% respectively of total MSW generated in the US compared wood and yard trimmings which accounted for 5.6% and 12.8% respectively (USEPA 2008). Technologies for converting all organic fractions of MSW into biofuels are reportedly available; e.g. gravity pressure vessel process from

Genesyst Inc . Walsh further adjusts the wood waste quantities downward by 53% to account for contamination by paints, chemical treatment, adhesives etc.

Our estimates of forest and mill residues consist of 55 million dt of logging residues and 80 million dt of mill residues. The logging residue estimates are very similar to those by Walsh. Walsh's assumption that 10% of mill residues are not usable because of too small particle size helps explain some of the difference in mill residue estimates. Additional differences may arise because Walsh's residue estimates are based on projected harvest rates for 2010, while our estimates are based on actual harvests in 2002. Enough details are not available to reconcile all the differences.

With regard to energy crops, Walsh projected 31 million dt by 2010 at a price of $110/dt. Our estimate is 85 million dt of energy crops at $100/dt. Her estimates are based on dynamic projections from the POLYSYS model. While POLYSYS model compares energy crop returns with field crop returns (similar to our approach), it also imposes various 'flexibility constraints.' For example, changes in acreages under different crops are limited to a maximum of 20% from previous year, and conversion of pasture lands to energy crops is accompanied by corresponding increase in hay crop output to meet animal feed requirements. In comparison, we employ a much simpler and cruder assumption that 10% of all cropland with current economic returns lower than switchgrass returns will shift to switchgrass. Further, in POLYSYS crop prices are determined endogenously within the model and hence are likely to be higher in the future, which makes energy crops relatively unattractive. Our ROVC estimates are based on historical costs. As a result, our energy crop supply estimates are higher and represent more optimistic estimates. The above comparison also demonstrates the sensitivity of the estimates to underlying assumptions and modeling, which can lead to large variations in biomass supply estimates across studies as pointed by).

2.4 Conclusions

The analysis suggests that more than 500 million dt of biomass is available at price of $100/dt in the US, while Canadian supplies are limited to 123 million dt. Assuming ethanol yields of 70-95 gallons of ethanol/dt, biomass quantity is sufficient to displace 27-37 billion gallons of gasoline in the US and 5.8-7.8 billion gallons of gasoline in Canada. Biomass quantities necessary to meet advanced biofuel provisions of EISA 2007 will be available at prices around $50/dt. Agricultural residues such as corn stover are the cheapest and most abundantly available sources of biomass followed by mill residues. Forest residues and energy crops are likely to play minor role in meeting EISA 2007 mandates. At current productivity levels, energy crops are not competitive with conventional crops in the prime agricultural areas of the US. However in some southern states such as Texas, Oklahoma and Tennessee energy crops may be able to compete with conventional crops and hence dedicated energy crop plantations are likely to appear first in these states. For example, a 1000 acre switchgrass plantation is being developed by Oklahoma Bioenergy Center, and University of Tennessee in contracting with farmers to grow switchgrass for the proposed Dupont-Danisco cellulosic ethanol plant . Energy crops may be more attractive in Canada because of relatively lower returns from traditional crops. Saskatchewan and Alberta will be major sources of both agricultural residues and energy crops, while British Columbia and Quebec will be major sources of forest and mill residues.

The estimates of agricultural residue supply are very sensitive to the assumed fraction of residues that can be sustainably removed from the field. Similarly the potential of MSW as a feedstock depends on which components (e.g. food, paper, wood) can be economically converted into liquid biofuels. Yields of energy crops need to improve significantly from current levels to make them competitive with conventional crops. Hence future research is needed in these areas. Finally the static supply function approach taken in this study, while is relatively simple and transparent, inadequately accounts for several factors that influence future biomass supplies such as productivity gains, harvesting and conversion technology improvements, inter-temporal variations in yields, costs and returns, policy interventions, and international trade effects. These limitations have to be kept in mind while interpreting and drawing policy conclusion from the reported results.

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REGIONAL COMPETITIVENESS OF ENERGY CROPS

3.1 Introduction

Cellulosic feedstocks such as agricultural residues, forestry residues, and dedicated energy crops (DEC) are predicted to become preferred feedstocks for biofuel production.[1] Crop and forestry residues are annually produced and available for immediate use; as a result their potential supply can be estimated. However, the potential for dedicated herbaceous energy grass crops such as miscanthus, and switchgrass is less certain because they are yet to be grown in large scale.[2] With a growing emphasis on energy crops to meet the cellulosic biomass requirements, one of the key questions is 'whether farmers will divert their lands from existing annual cropping practices to planting perennial energy crops?' This paper evaluates the economic competitiveness of energy crops with field crops and other land uses.

This study estimates the economic returns for farmers who divert their lands to energy crops versus the returns for farmers who retain their lands with the current crop uses. Since perennial energy crops supply biomass for 10 years, the economic returns from energy crops and other crops are compared over 10 years to account for economic fluctuations during that time frame. These fluctuations in economic returns arise primarily from changes in input and output prices which are affected by crude oil prices. In this study, I adopt a Monte Carlo simulation framework to analyze the impacts of crude oil prices on energy crop adoption. The simulation framework incorporates the

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[1] Currently, corn grains and soybean oil are used as primary inputs to produce biofuels; increased use of food and feed products for fuel production has generated interest in advanced biofuels such as cellulosic ethanol produced from cellulosic feedstock

[2] Perennial energy crops normally supply cellulosic biomass for 10 years

main factors that affect economics such as regional differences in crop yields, and differences in cultivation practices of field crops across various U.S. states.

Current literature compares energy crops with other agricultural crop enterprises largely based on point estimates (average values) of returns. But average returns do not capture the variability in energy and conventional crop profitability arising from crude oil price fluctuations and aggregate planting decisions of farmers. Fluctuating crude oil prices cause considerable uncertainty in the success of investments in cellulosic biofuels and the growth of energy crops. About 20 to 50 per cent of crop production costs are directly or indirectly tied to crude oil price level making it as a critical factor in the success of energy crops (Shoemaker, et al., 2006). Crude oil prices have varied between $20.87 and $127.34 per barrel (2010 dollars) between years….and… and preliminary evidence suggests that the cellulosic ethanol industry, and possibly energy crops, become economically attractive only if crude oil price stays consistently above $70 per barrel (Creyts, et al., 2007; EIA, 2010; Tyner and Taheripour, 2008). Schnitkey et al (2007) argue that the potential for biofuel feedstocks (including corn) should be evaluated by taking crude oil price fluctuations into consideration. With evidence that agricultural output prices – particularly corn, soybeans and cotton – have long run relationship with crude oil prices, it is important to study the impact of crude oil prices on the competitiveness of energy crops (Harri, et al., 2009; Modi, 2009). Crude oil prices affect the prices paid for energy crop biomass making it as a crucial determinant of the success of energy crops (Mark, et al., 2009).

I first develop state level crop production budgets for various field crops as well as energy crops over a 10 year planning period. Crude oil prices (COP) are a critical driver of relative returns because they affect the market prices of biofuels, energy crops and major field crops (corn and soybeans). Crude oil prices also affect the energy cost component (fuel and fertilizer) of crop production.[3] Prior literature suggests co-integrating long run relationships between crude oil prices, field crop prices and natural gas which is the main input in nitrogen fertilizer production (GAO, 2003; Harri, et al., 2009; Hartley, et al., 2007). Hence I first empirically estimate the historical relationships between crude oil prices, crop prices and the energy component of crop production costs (natural gas). I consider three crude oil price scenarios – reference case, high and low oil prices – as projected by USDOE over the next 10 years. Crop output prices and crop production costs are projected for each of these scenarios. Energy crop yields are modeled as a function of state level average climatic conditions (precipitation and temperature). Yields for conventional crops are projected using historical trends.

Second, I use Monte-Carlo simulation techniques to incorporate uncertainty into the static budgets developed above. I estimate the volatility (coefficient of variation) of projected crude oil prices as a weighted average of historical and implied volatility. The crude oil price volatility is assumed to drive the variations in crop production costs and crop prices. I simulate variations in energy crop yields assuming historical variances in precipitation and temperature continue into the future.

In the third step I consider crop switching decisions by farmers under different assumptions regarding their risk preferences. The results of the analyses are then used to predict the breakeven biomass prices necessary to make switching from current crops to energy crops attractive, and the probabilities that such switching will occur under the various crude oil price and farmer risk preference scenarios.

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[3] Crude oil prices affect natural gas prices which in turn determines nitrogen fertilizer prices

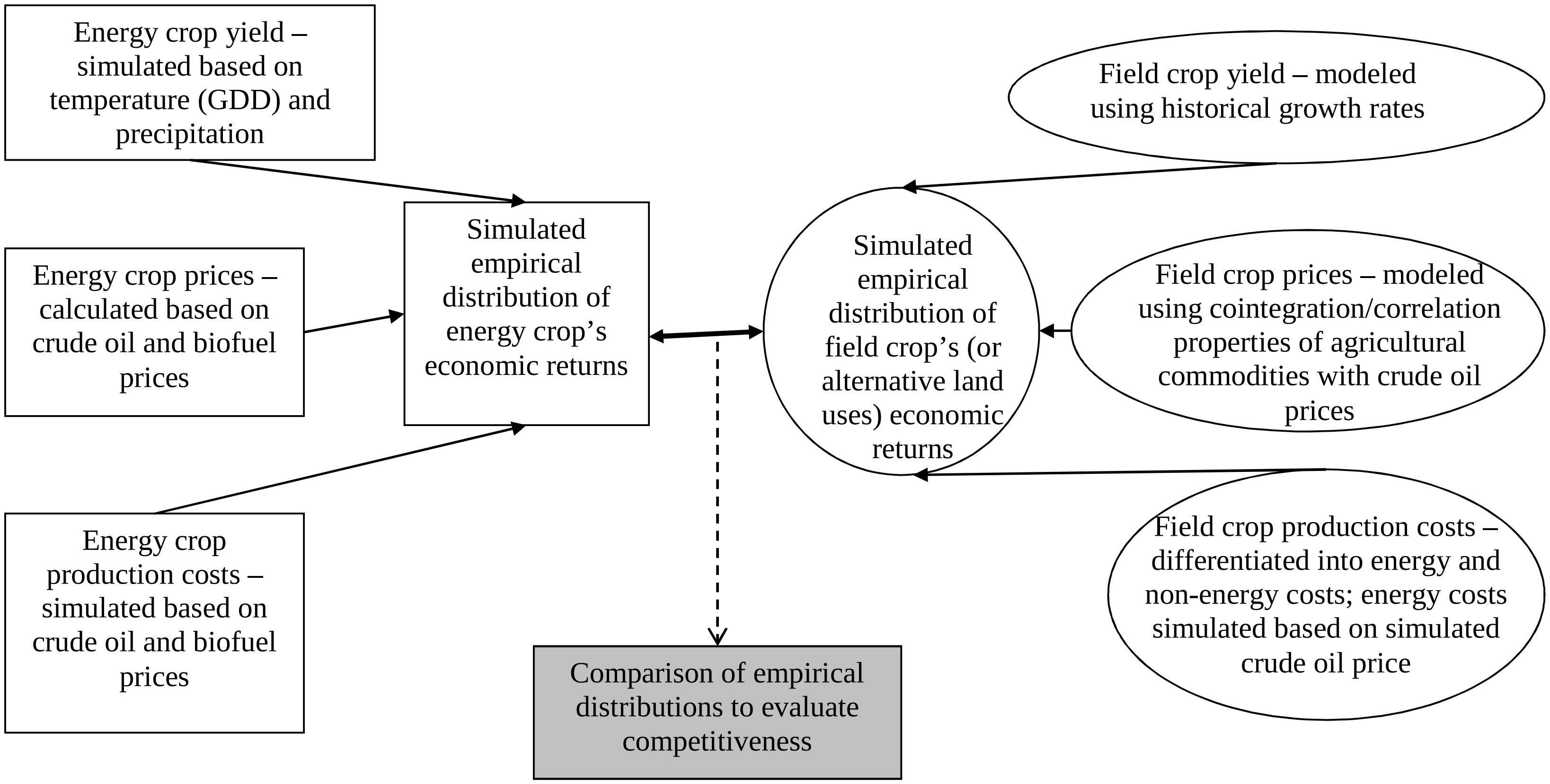
Objectives and Scope:

The primary objective of this analysis is to compare the economic returns of farmers who convert their fields to energy crops with the economic returns of farmers who retain their fields under existing crops. Another major objective is to identify the US states that have the greatest potential for energy crop production in terms of the average level and variability of returns. In particular, the research in this paper seeks to answer the following questions:

- How do the distribution of economic returns of energy crops compare with that of field crops across different states?
- What role do crude oil price fluctuations play in determining the economics of energy crops relative to traditional crops?
- How do state level differences in temperature (growing degree days, GDD) and precipitation affect energy crop (miscanthus and switchgrass) yield and returns?
- Which croplands (or fallow) are more likely to be converted to energy crops based on economic returns?
- How do risk preferences of farmers affect their energy crop production decisions?

These analyses are carried out at state level. The analytical steps in evaluating the relative economics of energy crops and conventional crops are summarized in Figure 3.1.

Figure 3.1: Framework of proposed simulation study:



3.2 Literature Review

A number of national level studies – that use a linear programming model called Polysys – evaluate the potential allocation of land to energy crops. Polysys models switchgrass yields based on hay crop yields at an agricultural statistical district level (ASD which is a collection of 9 or 10 geographically adjacent counties). These studies compare the economic returns of energy crops (switchgrass in particular) and field crops (De La Torre Ugarte and Hellwinckel, 2004; De la Torre Ugarte, et al., 2000; Ray, et al., 1998a, 1998; Walsh, et al., 2003). The Polysys studies predict that switchgrass will be competitive with field crops in 7 to 15 per cent of U.S. crop lands, supplying anywhere from 25 to 334 million tons of biomass per annum.The wide range of biomass estimates is a result of diverse assumptions used in Polysys modeling – see figure 3.2 and table 3.1 for a summary of major Polysys studies and their assumptions. By comparing Net Present Values (NPV) of energy crops and field crops, Polysys predicts a price of $32 – 74 per metric dry ton for switchgrass delivered at the biorefinery.

While the Polysys studies help generate estimates of crop switching and biomass supply at the level of individual agricultural statistical districts, these estimates suffer from many limitations. The analyses are based on deterministic (point) estimates of production costs and crop yields failing to include the fluctuations in production costs and returns. Polysys studies also suffer from data mismatch while computing NPV: the gross revenues from field crops are calculated using ASD data (groups of counties) but the production costs are estimated using USDA's Farm Production Regions (groups of states, see (De la Torre Ugarte and Ray, 2000; De la Torre Ugarte, et al., 2000).

Figure 3.2: Switchgrass production estimates – Summary of Polysys studies

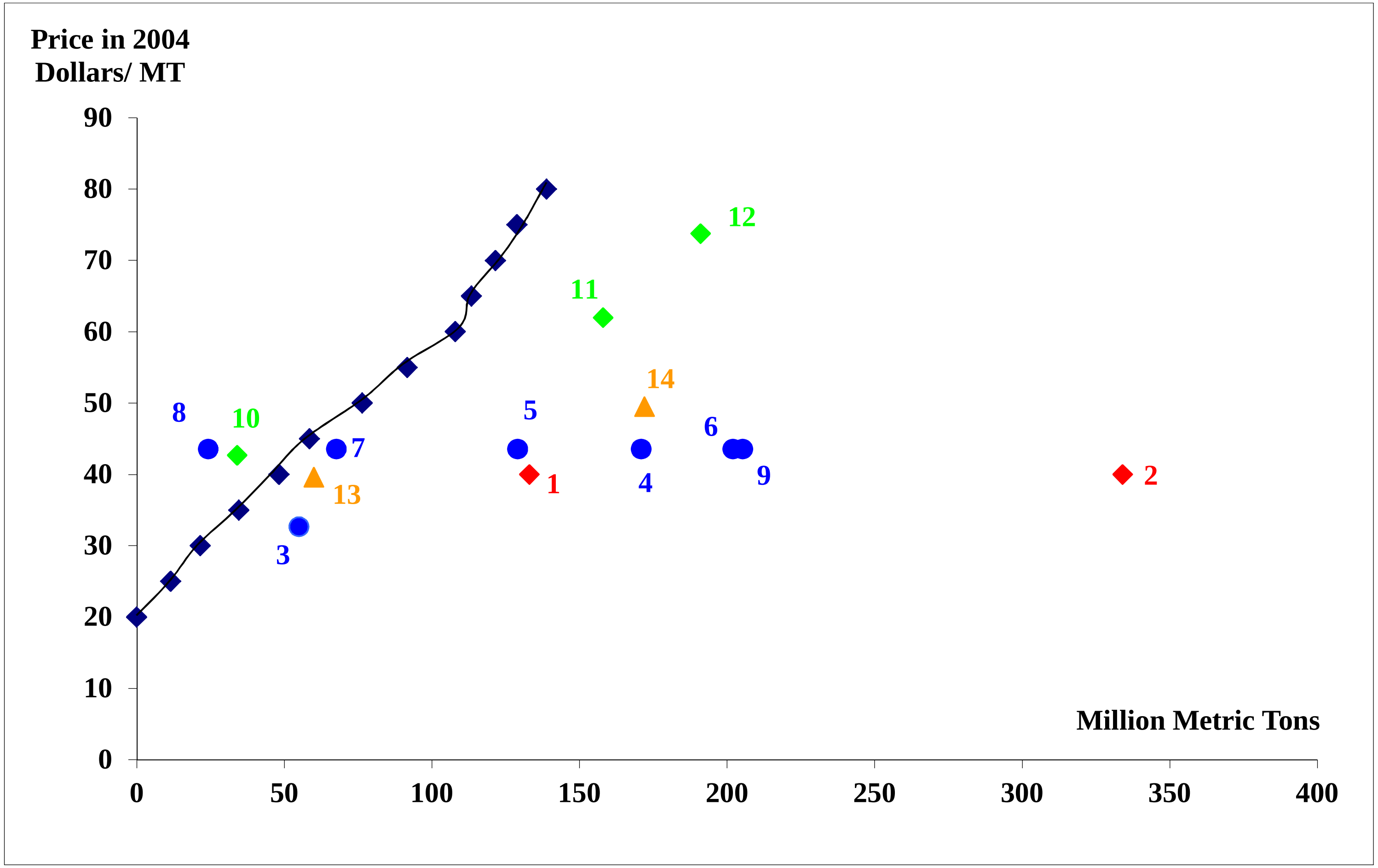


Table 3.1: Switchgrass supply curve – summary of different US national level studies

Study	Point	Quantity (Million Metric Tons)	Price (2004$)	Assumptions
De La Torre Ugarte and Hellwinckel (2004)	Line	0-139	0 – 80	2004 Farm Bill Provisions
Perlack, et al (2005)	1	133	40.00	Moderate crop yield with land use changes
	2	334	40.00	High crop yield with land use changes
Walsh, et al (2003)	3	54.9	32.70	Wildlife Management Scenario, $1.83/GJ
	4	170.9	43.60	Production Management Scenario, $2.44 /GJ
	5	129	38.15	Production Management Scenario, $2.14/GJ
	6	202	38.15	Production Management Scenario, $2.14/GJ, Switchgrass yield increases by 25%
	7	67.6	38.15	Production Management Scenario, $2.14/GJ, Switchgrass yield decreases by 25%
	8	24.2	38.15	$2.14/GJ, Cultivation costs increase by 25%
	9	205.3	38.15	$2.14/GJ, Cultivation costs decrease by 25%

Table 3.1 (Continued):

Study	Point	Quantity (Million Metric Tons)	Price (2004$)	Assumptions
McLaughlin S.B (2002)	10	34	42.70	Yield = 11 Mg/ha
	11	158	62.00	Yield = 9.4 Mg/ ha
	12	191	73.80	Yield = 9 Mg/ ha
De la Torre Ugarte, et al (2000)	13	60	39.60	1999 USDA crop yields, costs and prices
	14	172	49.50	1999 USDA crop yields, costs and prices

Polysys studies also use arbitrary land allocation constraints (called flexibility constraints) to avoid corner solutions resulting from the linear programming algorithm.[4] Polysys considers only switchgrass as the major energy crop while there are alternative energy crops such as miscanthus which yield higher than switchgrass and may be more competitive (Khanna, et al., 2008).

Few other studies have been conducted at the state level. These state level studies also compare the static net present values of energy crops with that of field crops – (Bangsund, et al., 2008; Cassida, et al., 2005; Guffey, 2006; Heaton, et al., 2008; Khanna, et al., 2008; Maryland Energy Administration, 2003; Perrin, et al., 2008; Vadas, et al., 2008). Except Griffith, et al., (2009), the existing studies assume a certain average level of energy crop yield and production costs in a state or region. Most of those studies implicitly treat energy prices to remain constant over the entire productive life period (10 years) of energy crops. These studies predict that energy crops can compete with field crops or other land uses if switchgrass prices (delivered at the biorefinery) are at least \$59.52-120 per dry ton in Tennessee, \$60-90 per dry ton in Iowa or \$54 per ton in Alabama and \$35-74 in North Dakota (Bangsund, et al., 2008; Guffey, 2006; Jensen, et al., 2005). These price estimates have a wide range due to different assumptions used in these state level studies.

These state level studies do capture regional variations by modeling the state level crop production practices and state level energy crop yields; but they cannot be generalized or aggregated to derive national level estimates due to variations in their underlying assumptions.

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[4] Polysys results are derived using ‘flexibility constraints’ that involve arbitrary assumptions on land allocation to energy crops (e.g. crop switching is limited at 15-20% of crop land – see section 2.5 in De la torre Ugarte, D. G., et al (2000) and section 3.1 in De la Torre Ugarte, D., and D. E. Ray (2000).

Most of the studies consider only switchgrass as the major energy crop while a few other studies evaluate miscanthus as a potential energy crop in the US. Farmers in some states (Tennessee and Oklahoma) have already adopted switchgrass as their prime energy crop due to lower establishment costs and easier seed based propagation. But other energy crops such as miscanthus may be more suitable due to higher yields even though their establishment costs are higher due to difficulties in propagation with rhizomes.[5] The differences in switchgrass and miscanthus yields and production costs are depicted in table 3.2 (Khanna, et al., 2008).

Table 3.2: Comparison of switchgrass and miscanthus crop yields and production costs in Illinois

	Switchgrass	Miscanthus
Cumulative yield over 10 years (dry tons per acre)	48.75	189.38 *
Establishment costs during years 1 and 2 ($/acre)	553.27	1099.19
Break-even price including transportation costs ($/ton) #	64.84	49.58

* Adapted for 10 year time frame; # excludes land rental costs; Source: Khanna, et al (2008)

The above discussion shows that there is a need to use a uniform framework while evaluating energy crops that accounts for fluctuations in crop revenues, yields and returns in a similar manner across all states. This study simulates budgets that is consistent across the states while incorporating the fluctuations in energy crop returns.

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[5] Agronomists and conservation experts suggest to grow switchgrass since they are native species to the US; miscanthus are native to European continent and has been successfully grown in many European countries.

3.3 METHODS

Crop production budgets and Net Present Value (NPV)

I use field crop production budgets developed by state extension agencies as a primary data source for my calculations. In particular, these budgets are used to derive the agricultural input quantities required for major field crops in every state (table 3.3). The agricultural inputs are divided into two groups – energy (s) and non-energy (x) inputs. The distinction between energy and non-energy inputs is made to extract the impact of energy (crude oil) price fluctuations on crop budgets. Energy inputs include diesel and fertilizers (N, P and K). Note that, fertilizers contain large quantities of embodied energy and their prices are closely linked to fossil fuel price movements. Non energy input costs include expenses on seeds, herbicides, pesticides, and fixed costs associated with buildings and machinery. Similar budgets for energy crops were developed by estimating the quantities of energy and non-energy inputs according to the maximum yield potential of energy crops at the state level.

A single planting of energy crop has an average productive period of 10 years. To match with this time frame, the returns from annual field crops are also estimated over 10 year time frame. This assumes that the particular field cropping pattern would be maintained over the next 10 years. To account for crop rotations, a weighted average of returns from two or more mono-cropping sequences is computed. The weights are determined by the relative frequency of the particular field crop in the crop rotation mix over a 10 year interval. The proportional changes in input quantities over 2000-2009 are used to compute the energy and non-energy inputs over the study period 2010-2019.

Table 3.3: Use of state level crop production budgets in computing NPV

X	This study (for years 1 through10)	Methods adopted in literature
Field crops or existing land uses		
Yield	NASS data on state level yields are projected according to their historic trend yields	Yield trends are incorporated in Polysys models
Crop Prices	Long run cointegrating relationships between crop and crude oil prices are used; in NPV calculations, crude oil prices are derived based on DOE-NEMS data	Derived as projections based on econometric or optimization models
Costs	USDOE – NEMS projections for crude oil prices are used	Energy prices are assumed to remain constant
Crop inputs/Energy (s_n)	Long run cointegrating relationships between crude oil prices and agricultural inputs (diesel, N, P and K) are used to predict energy input cost component	Impacts of energy prices are generally ignored
Non-energy (x_m)	Assumed to be constant within a state but allowed to vary across the states except for land rental values	No state level comparisons exist, generally non energy inputs are assumed to be constant
Economic returns in year t (F_t)	Price * Yield – (Energy costs + Non energy costs)	No distinction made between energy and non-energy costs
NPV	$\sum_t F_t(x_1, x_2, x_3, \ldots x_m; s_1, s_2, s_3 \ldots s_m)$	
Energy crops		
Yield	Derived based on a statistical model with state level temperature and precipitation as regressor	Based on state level plot studies or hay crop yields
Crop Prices	Derived as the residual value (defined as the revenues from biofuel in excess of processing and transporting costs)[6]	Break even prices are estimated based on costs of production
Costs		
Energy (s_n)	Energy inputs are assumed to vary with yield potential; energy input prices are derived similar to above	
Non-energy (x_m)	Assumed to be constant across states except for land rental rates	

[6] The residual values indicate the dollar value left to pay for cellulosic biomass after paying the processing and transport costs.

Table 3.3 (Continued)		
Economic returns	Price*Yield – (Energy costs + Non energy costs)	No distinction made between energy and non-energy costs
NPV	$\sum_t G_t(x_1, x_2, x_3, \ldots x_m; s_1, s_2, s_3 \ldots. s_m)$	

Comparison of crop budgets over a 10 years requires a metric such as Net Present Value (NPV) to account for the time preferences of farmers. The traditional NPV without any uncertainty is computed as

$$NPV_i = \sum_t \delta^t \text{ [Price}_{it} \text{ \$ per ton * Yield}_{it} \text{ tons per acre – Production Costs}_{it} \text{ \$ per acre]} \quad (A1)$$

Or $$NPV_i = \sum_t F_t(x_1, x_2, x_3, \ldots x_m; s_1, s_2, s_3 \ldots. s_m; \delta) \quad (A2)$$

where subscript i indicates energy crops (miscanthus, switchgrass), field crops (corn, soybeans, wheat, cotton) and other land uses (pasture, CRP); t stands for years t = 1, 2, … 10 (2010-2019), δ is the discount factor = $1/(1+\theta)$. Table 3.3 describes how the input cost components x and s are modeled in this analysis.[7] Many studies use these cost components to compute the break-even prices for energy crops (table 3.4 – A).

The Net Present Value is a common metric used to compare investment alternatives (Magni, 2002; table 3.4 - B). But NPV metric has limitations because there are additional sources of economic value that may arise from the flexibility to delay planting of energy crops. The ability to delay energy crop planting introduces additional value, termed as real option value.

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[7] Discount rate θ is assumed to be 2.01%; the discount rate is computed based on the yield of 10 year US treasury bonds (average of recent five year interest rate of inflation indexed bonds – (US Treasury, 2009). The discount rate captures the time preference of economic returns received by farmers over a 10 year time frame. The inflation indexed bond rates can be used to derive an estimate for θ since I compute NPV in terms of constant dollars (2009 dollars). I use 10 year US treasury bonds because energy crops normally have a productive life of 10 years. Note that the subscript 'i' can also represent a crop rotation (for example, combination of corn and soybean crops such as CS or CCS) repeated over a ten year period

Such additional economic values will alter farmers' land allocation decisions (table 3.4 – C). However, the current approach of using NPV with uncertainty remains useful for a number of reasons. The option value of delaying planting energy crops will be similar for farmers in different US states for the following reasons.

Table 3.4: Possible metrics to evaluate economic competitiveness of energy crops:

Criterion	Evaluation Metric	Remarks
Energy crops alone		
A	Break even prices for energy crop production costs	Calculated over 10 year time period of energy crop's productive life (e.g. Brummer et al)
Comparison with other land uses		
B	Net Present Values (NPV) of energy crops compared with that of field crops	No uncertainties accounted for (e.g. Vadas et al, Polysys studies)
C	Expanded NPV criterion with option to delay (real options framework)	e.g. (Song, et al., 2009)
D	Empirical distributions of energy crop NPV and field crop NPV	Uncertainty in input and output factors (e.g. fluctuating crude oil prices – this study)
Others		
E	Account for available price hedging mechanisms for energy crops in comparison with field crops	Contracting terms between biofuel plants and farmers
F	Account for current and potential government incentives and policy variables.	Not included in the current analysis

Once a biorefinery has been planned for a site, the biorefineries promote and support immediate establishment of energy crop biomass which attenuates real option values in energy crop plantations. The biorefineries are located based on the ability for local farmers to supply feedstocks consistently (Robb, 2007). The efforts of the biorefinery in writing long term contracts, providing on-farm cultivation support and ensuring proper supply chains for energy crop production delivery reduce the real option values associated with delaying the planting of energy crops. Other reasons are explained in appendix A. The analysis does not include hedging because hedging is a short run risk management option and less relevant for long term crop switching decisions. The role of government policies are excluded from the model because the goal of the analysis is first to figure out how the market emerges in the absence of such support policies. However the impacts of such support systems are discussed in the conclusions.

NPV with Uncertainty

With no uncertainties, the cost components (both $x_1, x_2, x_3 \ldots x_m$ and $s_1, s_2, s_3 \ldots s_n$) are well known and NPV turns into a deterministic metric. Such deterministic measures have been the focus of the existing studies in evaluating the suitability of energy cops but they are not very informative given the random fluctuations encountered in crop production costs especially the energy cost component. This problem can be overcome by modeling fluctuations in some or all cost components and simulating the distribution of NPV. I introduce such fluctuations in this analysis by modeling energy cost ($s_1, s_2, s_3 \ldots s_n$) fluctuations based on crude oil price movements. Dimakos, et al., (2006) shows the conceptual background of joint estimation of stochastic variables to derive *NPV with uncertainty* (table 3.4 – D). This method is particularly helpful when uncertainty is a critical factor in the success of a proposed new enterprise such as energy crops. For instance, Grove, et al., (2007) use such stochastic budgeting methods to evaluate the profitability of converting crop-animal farm into a hunting range where the economic returns from the proposed hunting range is not known with certainty. These stochastic budgets are also useful in computing the consistency (in terms of probability) of generating higher economic returns from switching to energy crops (Kleiber, 2009).

In my analysis, stochastic budgeting technique works as follows: a specific value for crude oil price (dollars per barrel) is simulated for each iteration. The simulated crude oil price is used to simulate estimates of energy costs, commodity prices, and NPV of energy crops and field crops. The crude oil prices variations are generated for three different scenarios – reference case, high and low crude oil price cases (EIA, 2009). The empirical distribution of crude oil prices are derived based on log normal distributional assumption. The crude oil prices are simulated using a log-normal distribution with mean values derived from EIA estimates. The standard deviation of crude oil price distribution is derived from the volatility estimates using a weighted average of historic and implied volatility. The weighted average approach helps utilize most of the available information both from the past (historic volatility) and about the future (implied volatility). The energy cost components of crop production (diesel, N, P, K fertilizer prices denoted by $s_1, s_2, s_3 \ldots s_n$) are simulated based on their long run cointegrating relationship with crude oil prices (where applicable) and their historical correlations. Other non-energy inputs ($x_1, x_2, x_3 \ldots x_m$) are maintained constant with every iteration. This helps isolate the impacts of energy cost variations. But the non-energy inputs are allowed to vary across states to reflect the differences in production practices and land quality. Repeated simulations of the budgets for various draws of crude oil prices generate an empirical distribution for NPV_i. This enables the comparison of empirical distributions of energy crops' NPV with that of field crops.

I use probability measures to compare the distributions and to measure the consistency of generating higher returns with energy crops. It compares the consistency of receiving higher returns from energy crops with that of existing crop rotations. The consistency of economic returns from energy crops is important because the study simulates crude oil prices along with other factors. The consistency is measured by comparing the empirical distributions of NPV values of both energy crops and field crops. If the probability of receiving higher economic returns from energy crops is higher than the existing land uses, then energy crops can be declared to be competitive in that state compared with the traditional crops. The probability measure thus becomes a measure of the variance of NPV values.

Climatic Factors and Crop Yields

One of the prime determinants of returns is yield of energy crops and field crops . Surveys show that energy crop yield is a key drivers of energy crop adoption (Anand, et al., 2009; Jensen, et al., 2005). Switchgrass yields in Tennessee average 8 to 10 tons per acre per year while Iowa switchgrass yields are only half of that, due to differences in climatic factors (temperature (GDD) and precipitation). Since climate plays a major role in determining energy crop yields, I use a statistical model that estimates energy crop yields as a function of state level temperature and precipitation data. It is common to model crop yields based on climatic factors (Lobell, et al., 2006). With regard to energy crop yields, Ivanic (2008) uses a statistical model of regional temperature and precipitation to estimate the potential yields of switchgrass and miscanthus in any location.[8] The estimates of the regression model are presented in table 3.5; all coefficient estimates are significant at 1 per cent level showing the high impact of temperature

[8] Miscanthus is high yielding crop non-native to the US propagated through rhizomes at higher production costs; switchgrass is a native prairie grass already grown in CRP lands and easily propagated through seeds at lower production costs. Ivanic (2008) study uses yield data from 16 plots for switchgrass: Arkansas (1 plot), Illinois (5), Louisiana (1), Mississippi (1), North Dakota (4), Texas (3), and Tennessee (1); for miscanthus, yield data from 24 plots are used: Illinois (6), Mississippi (1), and international locations (Austria (1), Canada (2), Denmark (1), Germany (5), Ireland (1), Netherlands (2), Poland (3 plots), Sweden (1), and Turkey(1)).

and precipitation on energy crop yields. Although simplistic, Ivanic's model provides a reasonable way to predict energy crop yields; the temperature and precipitation factors explain 70% of energy crop yield variations (see the last column on R^2 values in Table 3.5). In comparison, advanced biophysical models such as ALMANAC that use micro (field) level information on temperature, rainfall, soil characteristics such as soil water balance, soil and plant nutrient balance, and interception of solar radiation explain about 80% of energy crop yield variations which is only a slight improvement over Ivanic's model (Kiniry, et al., 2005; Kiniry, et al., 1996; Kiniry, et al., 2008).[9] These statistical models can yield representative estimates of energy crop yields at state level and have already been used by other researchers to conduct state or county level studies (Khanna, 2009). Table 3.5 results show that miscanthus yields will be consistently higher than that of switchgrass in all states – which reiterates the results presented in table 3.2.

Table 3.5: Maximum potential yield of energy based on temperature and precipitation

Energy Crop Yield (metric dry tons per acre per year)	Regression of yield on temperature and precipitation	R^2 value
Switchgrass	2.2 + 0.02 * (GDD * Precipitation) / 1000	0.69
Miscanthus	6.6 + 0.04 * (GDD * Precipitation) / 1000	0.71

Source: Ivanic (2008); all coefficient estimates are significant at 1 per cent level

[9] Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model use information on temperature, rainfall, soil characteristics such as soil water balance, soil and plant nutrient balance, and interception of solar radiation to predict energy crop yields at micro (field) level

Crude oil price and agricultural input prices

The economics of energy crops or field crops have to be studied over a 10 year time frame.[10] Crude oil prices fluctuate within a 10 year period which also leads to fluctuations in energy costs (e.g. diesel and fertilizer inputs) in agriculture. The amount of energy inputs vary across crops, leading to differential impact of crude oil price fluctuations on crop production costs. Higher diesel prices result in higher transportation costs in agricultural operations (Huang, 2009; Olczyk, et al., n.d.). There is growing evidence that natural gas prices exhibit cointegration ('stable long run (positive) relationship') with crude oil prices (Hartley, et al., 2007; Shoemaker, et al., 2006); since natural gas price accounts for 70-90 per cent of nitrogen fertilizer production costs, crude oil price fluctuations indirectly affect nitrogen prices as well (GAO, 2003; Huang, 2009). To incorporate these long run cointegration relationships, I empirically estimate diesel and nitrogen prices as a function of crude oil price (COP, 2009 dollars) and natural gas price respectively as given below (standard errors are in parentheses).To forecast diesel prices based on crude oil prices, the weekly data on diesel and crude oil prices from January 1997 to January 2009 was used. To forecast nitrogen prices based on natural gas (which is cointegrated with crude oil prices), the annual data from 1997 to 2005 was used. Both regressions used ordinary least squares method.

Real Diesel price (2009 \$/gallon) = 1.305 + 0.021 * COP ($R^2 = 0.91$)
(0.11) (0.0002)

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[10] The energy crop yield pattern gradually increases in the first two years, stabilizes and reaches a potential maximum during years 3 through 7, and gradually declines in years 8 through 10 (Angelinia, et al., 2009). Over this 10 year time frame, the revenue uncertainty is high for both field crops and energy crops. Even though there are futures markets for field crops to hedge against uncertainty, those markets extend only 2 or 3 years into the future; no such markets exist for energy crops.

The cost of N fertilizer is calculated based on natural gas prices:

$$\text{Real Nitrogen price (2009 \$/lb)} = \underset{(0.044)}{0.253} + \underset{(0.007)}{0.019} * \text{NG price} \qquad (R^2 = 0.51)$$

where NG price refers to natural gas price ($/million BTU). The relationship between natural gas and crude oil prices, as reported by Hartley et al. (2007- pp: 24), is given below:

$$\ln P_t^{NG} = -0.1872 + 0.8460 \ln P_t^{WTI} - 3.0032 \ln [HR_t^{NG}/HR_t^{RFO}]$$

where t is the time subscript, P^{NG} is natural gas price ($/MMBTU), P^{WTI} is crude oil price (West Texas Intermediate type), HR^{NG} is heat rate of natural gas, HR^{RFO} is heat rate of residual fuel oil (a derivative of crude oil that is a substitute for natural gas). I use the above equation to derive natural gas price based on the simulated crude oil price. This price relationship holds in the '*long run*' (italics as given in the Hartley et al.) which suits my purposes of forecasting NG prices over 2010-2019. The heat rates for 2010-2019 are forecast using an ARIMA(1,1,0) model at annual intervals. In spite of high correlation coefficients reported in table 3.6, there is no evidence for long run cointegrating relationship between Crude oil prices, Phosphorus (P) and Potassium (K) fertilizer prices (Huang, 2009). I simulate P and K prices based on their historical correlations with N fertilizer prices; i.e. there is no causal relationship between crude oil price fluctuations and P or K fertilizer prices. I implicitly assume that the historical probability distribution of NPK fertilizer prices will continue into the future. The mean and standard deviation of P and K prices are derived from their time series price data. The temporal correlations between the three major fertilizers are presented in table 3.6.

Table 3.6: Correlation between crude oil price and NPK fertilizers (1989-2008)

	N price	P price	K price	COP
N price	1.000			
P price	0.925	1.000		
K price	0.938	0.990	1.000	
COP	0.959	0.933	0.956	1.000

Crude oil and agricultural output prices

Crude oil prices determine the output prices paid for energy crop cellulosic biomass and field crop grains. The maximum prices paid for dedicated energy crops depend directly on ethanol prices, which in turn depend on gasoline prices, crude oil prices and biofuel processing costs (EIA, 2008a; Kumarappan and Gustafson, 2009; Mark, et al., 2009). Gasoline prices is derived based on simulated crude oil prices as following; the monthly US DOE – EIA data from January 1986 to December 2008 was used to estimate the following regression estimates:

$$\textit{Gasoline price (2009 \$/gallon)} = \underset{(0.040)}{0.915} + \underset{(0.001)}{0.027} * COP - \underset{(0.00001)}{0.000032} * (COP)^2$$

Ethanol price (2009 $/gallon) is computed as 0.70 * predicted gasoline price. Then, energy crop biomass price (2009 $/ton) is computed as [Ethanol price ($/gallon) * Ethanol yield (gallons/ton) – costs for pretreatment, processing, and transport ($/ton)]. The above equations show how the prices paid for energy crop biomass depend on the simulated crude oil price. Ethanol yield from cellulosic biomass is assumed to be 80 gallons per ton. The pretreatment and processing costs are assumed to be $1/gallon. This is slightly above the target processing costs for cellulosic biofuels to be competitive with crude oil (DOE-EERE, 2010). Khanna et al (2009) uses a similar assumption; note that the results are sensitive to this assumption. I discuss the implications of alternative processing costs in the results section. The transport costs were assumed to be $10/ton.

Harri et al., (2009) show that crude oil prices affect (Granger-cause) corn and soybean prices in the US especially after 2006. Other studies also find evidence of co-movement of energy prices and agricultural commodity prices in the US (Benjamin, et al., 2009; Campiche, et al., 2007; Du, et al., 2009; Zhang and Reed, 2008).[11] Such cointegrated price movements and correlations between crude oil (or energy) and agricultural commodity prices are likely to continue in the future given the continued reliance on corn ethanol over the next 15 years (EISA, 2007).[12] The cointegrating long run regression relationships between corn, soybean and cotton prices and crude oil prices are estimated using monthly data after April 2006. The super consistent estimates from ordinary least squares (OLS) regression of commodity prices on crude oil prices and currency exchange rates are used for my calculations. The prices for other crops (wheat, sorghum, pasture, fallow or CRP), which are not found to be cointegrated with crude oil prices are simulated as correlated time series. It is a valid approach for the following reasons: as explained for P and K fertilizers, the historic correlations between these crops and crude oil prices can be expected to continue in the future; it ensures consistency that crude oil price fluctuations are incorporated as part of the other crops; and using correlated simulations is a common practice to model temporal data.

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[11] Although these results are found in the US, some international studies find no relationship between crude oil prices and commodity prices in other countries – (see Benjamin et al, 2009; Zhang and Reed, 2009)

[12] Corn ethanol production is currently at 11 billion gallons per year – EISA requires corn ethanol to be capped at 15 billion gallons per year during 2015-2022

A major limitation of this approach is that the past correlations are expected to continue in the future without any changes. It is difficult to predict crude oil prices and even more difficult to predict the correlation of crude oil prices with agricultural, and energy commodities in the future. One reasonable approach is to modify the historical correlations and use it for projecting in the future. Since the cointegration between crude oil prices and agricultural commodities is a recent phenomenon (starting in 2006), there is a lack of data to predict correlation values in the future. So, the historical correlations are assumed to continue into the future; the results have to be interpreted recognizing this limitation.

Simulating crude oil prices

For the purposes of this study, crude oil prices over the next 10 year time frame (2010-2019) are required at annual intervals. I use the crude oil prices projected by US-EIA's National Energy Modeling System (NEMS – see figure 3.3). NEMS data provides long term forecasts based on international energy market supply and demand conditions (EIA, 2009, 2003).[13] NEMS model is widely used for national and international policy making, including that of USDA analysis (USDA, 2009).[14] Its forecasts are reliable because they anticipate alternative economic growth scenarios and project crude oil prices corresponding to three scenarios: low, reference case and high price scenarios (see figure 3.3, and table 3.7). In the reference case, the crude oil price ranged from $49/barrel in 2010 to 112/barrel in 2019; in low price scenario, the crude oil prices are expected to decline slightly from $55 to $47/ barrel over 2010-2019; in high

[13] NEMS forecast are classified under high/low economic growth, high/low world oil price to reflect various levels of crude oil prices. I used the former classification.

[14] USDA analysis drives the policy behind subsidy for energy crop biomass (BCAP, EIA 2007)

price scenario, crude oil prices are expected to increase from $88 to $178/barrel over 2010-2019.[15] The NEMS model provides only the average price levels; the price fluctuations or volatility around these average price levels have to be modeled for conducting simulations underlying this analysis.

Figure 3.3: NEMS forecast of crude oil prices 2010-2019 ($/barrel):

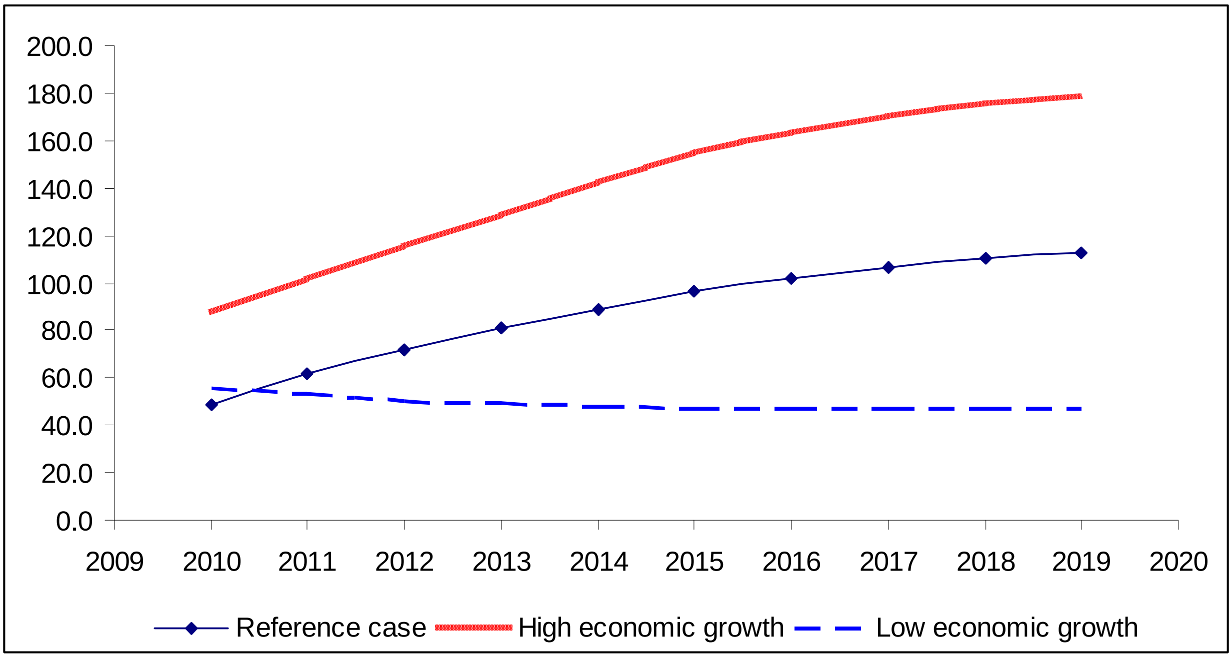

Table 3.7: Three scenarios of crude oil prices ($/barrel)

Scenario	Crude Oil Price Range 2010-2019 (2009 dollars) *	Crude Oil Price Volatility (in terms of coefficient of variation) #
Low economic growth (I)	$55 - $47	From 36% in 2010 to 26% in 2019
Reference case (II)	$49 - $113	From 36% in 2010 to 24% in 2019
High economic growth (III)	$88 - $178	From 36% in 2010 to 23% in 2019

* these values are depicted in figure 3.6; Source: DOE National Energy Modeling System
# these estimates are based on historical and implied volatility figures explained below.

[15] Inflation index between 2007 and 2009 is 1.04; i.e. $1 in 2007 is equivalent to $1.04 in 2009

Estimating crude oil price volatility

For my purposes of projecting crude oil price volatility over 10 years, I use a weighted average of two volatility measures (historical volatility as described above and implied volatility) that contain information about long term volatility movements in crude oil prices. The weighting procedure is explained in Appendix B. Such a combined estimate is considered to be a more reliable predictor compared to single estimator (Armstrong, 2001; Poon and Granger, 2003).

Volatility of any price series is defined to be "the standard deviation of the continuously compounded rates of return… over a specified period" which is "the same as the standard deviation of the differences in the natural logarithms of… prices… over the period" (FASB, 2004). A commonly used volatility measure is derived using historical data. For example, if crude oil prices changed from C_1 to C_2 at a continuous compound rate r over a period of time t; i.e. $C_2 = C_1 e^{rt}$, then volatility, expressed in percentage terms, is defined as the standard deviation of the series r. It is interpreted as coefficient of variation (volatility (%) = standard deviation/mean).[16]

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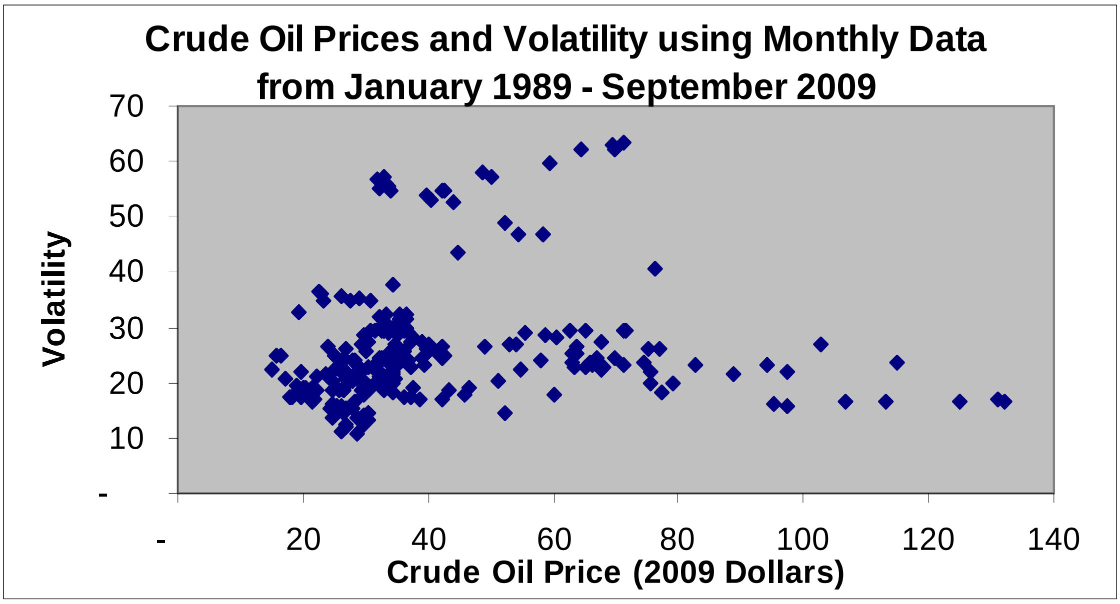
[16] Hence, the continuously compounded rate of return (r) is $r = (1/t) * [\ln (C_2 / C_1)]$. The volatility of price series C over the period t is given by the standard deviation of the series r, i.e., $(1/\sqrt{t})*$***stdvn***$[\ln (C_2 / C_1)]$, where ***stdvn*** stands for standard deviation. To express it in annualized terms (t = 1 year), I multiply the above expression with $\sqrt{t}$ to get the expression ***stdvn***$[\ln (C_2 / C_1)]$ or ***stdvn***$[\ln (C_2) - \ln (C_1)]$. Volatility in terms of standard deviations (dollars per barrel) is obtained by multiplying the volatility estimate (%) for a particular year with the mean crude oil price estimate given in figure 3.5.

Figure 3.4: Spot prices volatility of crude oil prices – January 1989-September 2009



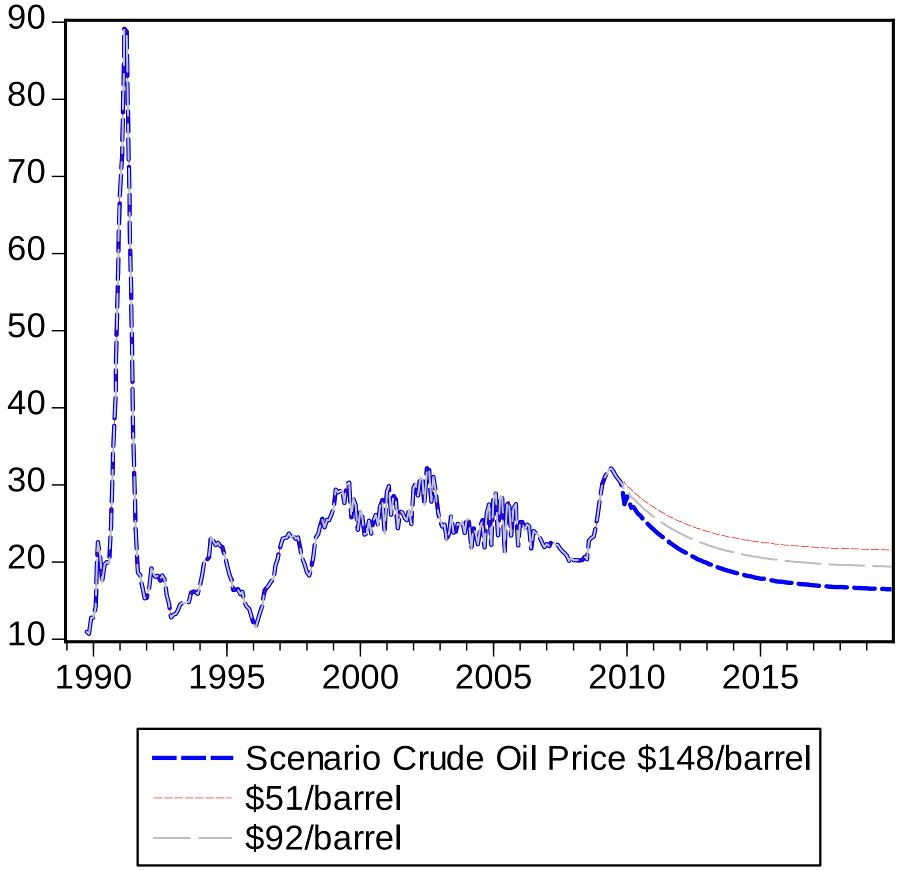
The distribution of crude oil prices is heteroskedastic since volatility (a measure of variance) varies with the level of crude oil prices. The crude oil price fluctuations vary inversely with crude oil prices; i.e. volatility is more when crude oil prices are low and vice-versa (figure 3.4). The time series data for historical volatility estimates is forecast for 2010-2019 using GARCH models.[17] Following Agnolucci (2009) I model the historical price volatility as a GARCH(1,1) process; this process is shown to perform better than other competing processes, in terms of lowest mean absolute error (MAE), and mean square error (MSE, for more information see (Agnolucci, 2009; Manfredo, et al., 2001). This regression is used to forecast historical

[17] There are other ways to model volatility of commodity prices that include stochastic volatility, Monte Carlo Markov Chain (MCMC) methods, implied volatility, crack spread futures, regime switching stochastic volatility and pattern matching methods (Andersen, et al., 2005; Fan, et al., 2008; Figlewski, 2004; Murat and Tokat, 2009; Sadorsky, 2006; Vo, 2009; Yu, et al., 2008; Zhang, et al., 2008). Many of these methods focus on explaining past regime shifts, or rapid increases in prices, or sudden changes in price volatility rather than focusing on the future.

volatility estimates (HV_f) for the years 2010-2019. Inclusion of crude oil price as an exogenous regressor in the GARCH model also helps differentiate the projected historical volatility based on the level of crude oil prices (see figure 3.5). Historical volatility explained above contains only past information. Information about the future crude oil price variations can be derived using an implied volatility measure.

Implied volatility (IV) is computed using options on crude oil futures contracts. IV refers to the underlying volatility that results in the observed premium price for options. It is obtained by inverting the Black equation used for pricing options on futures contracts. Options on crude oil futures are actively usually traded for three years (2010-2012) into the near future . Hence, I can estimate the implied volatility measures based on options premiums for all months in 2010-2012 (IV_f). But, the implied volatility estimates are required for all the years between 2010 and 2019. To forecast the IV estimates for the years of 2013 through 2019, I project the IV data from 1993 through 2012 using a GARCH(1,1) model. Agnolucci (2009) adopted this method while comparing alternative procedures to forecast crude oil price volatility. The time series data obtained from CRB (2009) is used for forecasting implied volatility which is explained in Appendix C.

Figure 3.5: Historical volatility forecast (percentage) – low, reference and high crude oil prices scenarios

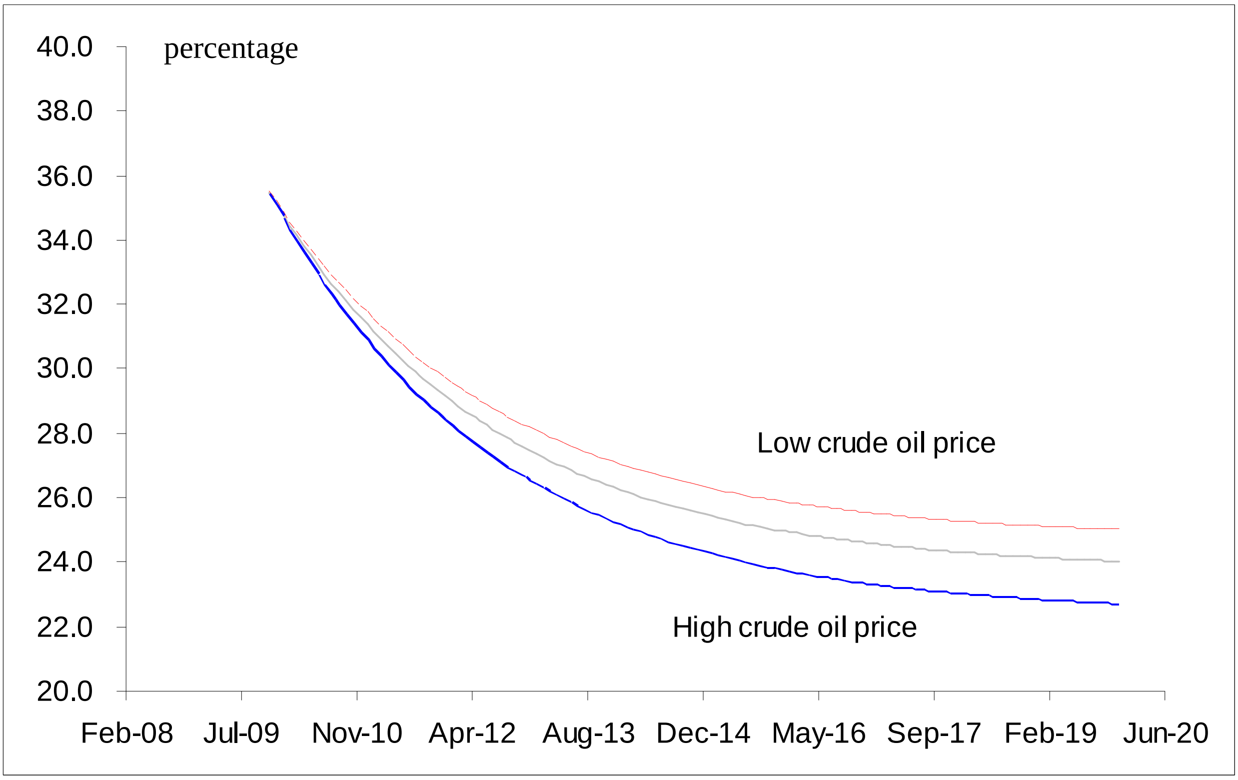


The volatility estimate used to simulate crude oil prices are derived by weighting IV_f and HV_f values. The weights are derived using the procedure suggested by Granger and Ramanathan (1984): the weights are the OLS coefficient estimates of the regression of realized spot price volatility on the historical time series data of historical volatility (HV_p) and implied volatility (IV_p). The data for this regression pertains to monthly data during 1993-2009.[18] Agnolucci found that including a constant in the above regression is appropriate for modeling crude oil price volatility. The procedure is explained below. The weights are actually the least squares

[18] The past data on implied volatility is available starting from 1993.

coefficient estimates ω_0^, ω_1^, ω_2^ from the regression $r_t = \omega_0 + \omega_1 IV_p + \omega_2 HV_p + \varepsilon$, where r_t is the spot price volatility estimate calculated as $\ln(S_t/S_{t-1})^2$ using daily data for years 1993 – 2009, S_t is the spot market price of crude oil at time t, IV_p is the past data on implied volatility (based on options on crude oil futures contract) for years 1993 – 2009, HV_p is the past data on historical volatility (based on futures contract prices) for years 1993 – 2009, and ε is the White's noise ~ N(0,1).[19] The time series data on IV_p and HV_p are obtained from Commodity Research Bureau, CRB (2009). The weighted volatility measure (expressed in percentage) can also be interpreted as coefficient of variation, i.e. standard deviation divided by mean (figure 3.6).

Figure 3.6: Weighted volatility forecast – low, reference and high crude oil prices scenarios



[19] Among GARCH models, single equation ARMA-GARCH model is found to be better predictor of historical volatility than other GARCH models (see Padorsky, 2006); Actual IV data exist for years 2010-2012 – so the forecast for those years were not used in the analysis

For illustrative purposes, standard deviation of crude oil price for 2014 is derived as following: standard deviation for 2014 = weighted volatility measure for 2014 * mean price of crude oil for 2014. Figure 3.6 shows that the price volatility is (slightly) higher when crude oil prices are low confirming the inverse relationship depicted in figure 3.4. Implied volatility computations (based on Black equation) assume that the future crude oil prices possess log-normal distribution. I retain the same distributional assumption for simulating crude oil prices using mean price levels (figure 3.3) and volatility (figure 3.6) described above.

Simulating energy crop yields

The yield potential of energy crops is simulated using historic state level data on temperature and precipitation. Since the climatic factors do not vary considerably within a state or region, historic information is useful data to project or simulate future temperature and precipitation values. The range (minimum and maximum) of values for temperature and precipitation during 1970-2008 was used for simulation purposes (Appendix D). With regard to climatic variables, this is rather a large time span over a large geographic area such as state. Hence, any value from this range of values (between the minimum and maximum values) will appear in the future. Under this assumption, a uniform distribution is valid to simulate temperature and precipitation. I simulate state level temperature and precipitation data at annual intervals which satisfy the above criteria, i.e. assuming uniform distribution (Dempster, 1999; Mehrotra, et al., 2006).[20] The historical correlations between temperature and precipitation are

[20] Note that uniform distributions do not fit smaller geographic locations (a single farm or zip code) or smaller time frame (within an hour) – but it is a reasonable approximation over large geographic areas (state) at annual intervals that use non-seasonal data. The use of 30 year historical data ensures that the simulation of temperature and rainfall over 10 years into the

maintained in simulated data. The yield of miscanthus and switchgrass is computed using the simulated temperature and precipitation data and the parametric estimates in table 3.5. The actual yield of energy crops would be low at the start and end of the 10 year productive time frame: 30% of potential yield in year 1, 70% in year 2, 100% in years 3-7, and 80% in years 8-10 (Angelinia, et al., 2009).

Simulating field crop yields

Historical field crop yield data for individual states are available from USDA.. The time series data for field crop yields corresponding to years 1970-2009 are found to be trend stationary time series processes. Hence, I use trend projections to forecast the field crop yields during 2010-2019. The growth in field crop yields is modeled using Compound Annual Growth Rates (CAGR) because they are found to be better than linear or exponential extrapolation procedures when the increase in yields are deterministic (Reilly and Fuglie, 1998; Taher and Shadmehri, 2008). Reilly and Fuglie (1998) note that CAGR computed using only one set of initial and final time points can be misleading. To overcome this problem, I derive CAGR for every 10 year time slots: i.e. a CAGR estimate for 1970-79, another estimate for 1971-1980, and so on. The average of all CAGR estimates is used to forecast field crop yields over 2010-2019. My approach implicitly assumes that there will be no major technological breakthrough altering the yield of field crops over the next ten years.

Simulating energy crop production costs

Nitrogen fertilizer is a major input in energy crop production. The maximum yield for energy crops is attainable when nitrogen fertilizer is applied at a rate of 10 pounds per ton of

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future will remain valid. Non-uniform distributions are needed only in micro-field level simulations, which is not the case here.

potential cellulosic biomass yield (Perrin, et al., 2008; Vadas, et al., 2008); but the fertilizer responsiveness of energy crop yields to nitrogen application flattens out beyond 70 lbs/acre (Jain and Erickson, 2008) – hence, the amount of nitrogen applied for energy crops is 70 lbs or less depending on the potential yield in a state. The other fertilizers (P and K) are required only in the initial years of energy crop establishment. The energy inputs required for energy crop production are given in table 3.8. The input rates for diesel, phosphorus and potassium are assumed to remain the same across all states. The nitrogen input rate alone is varied according to the maximum biomass yield possible within the particular state.

Table 3.8: Energy input use for energy crop production

Energy Input	Quantity
Diesel (gallons/ton)	2.1
Nitrogen (lbs/ton)	10 (capped at a maximum of 70 lbs/ac)
Phosphorus (lbs/ac)	18
Potassium (lbs/ac)	36

Source: Ivanic (2008)

The non-energy inputs such as seeding, reseeding, machinery, chemicals (pesticides and herbicides) and harvesting are assumed to be constant: the seed material costs were assumed to be $22.40 per acre in the first year and $2.40 per acre for subsequent years for reseeding in all states; the fixed costs associated with machinery and non-energy inputs were estimated to be $164.44 per acre for all years 1 – 10 (Perrin, et al., 2008). The land rental rates for energy crops will be the same as that estimated for field crops (USDA - NASS, 2007).[21]

[21] In simulation studies, it is common practice to assume simpler distributions that require fewer parameters when there is limited information available (such as land values, in this case).

Simulating field crop production costs

The energy and non-energy inputs of field crop production were derived from crop production budgets generated by the state extension agencies. For every state in the study region, the energy input quantities were multiplied by their corresponding simulated prices to derive the crop production cost. The quantities of energy inputs are assumed to remain the same over 2010-2019. This assumption eliminates any input substitution that could result due to changing crude oil prices. The non-energy cost component (seeds, chemicals and pesticides) are fixed constant for every state (see table 3.3).[22] The land rental value for field crops are derived from NASS reports (USDA - NASS, 2007). At the national level, the rental value for pasture is found to be one third of prime cropland rental value. The list of crop production budgets from different state extension agencies is given in Appendix E.

3.4 Role of Risk Aversion in Energy Crops Adoption

Aggregate utility function

Risk averse farmers derive different levels of utility depending on the riskiness of energy crops vs. field crops. To study the impact of risk aversion on a representative farmer as in this study, I transform the NPV measure to reflect farmers' risk aversion level. I use concave utility function to model the behavior of a representative risk averse farmer. The study of a representative farmer generalizes the results for the entire state. Hence, the concave utility functions can also be interpreted as aggregate risk averse utility functions commonly used in macroeconomic studies (Pindyck, 1986; Saltari and Ticchi, 2007).

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[22] Only the states in the eastern half of US were considered; the western states were not considered due to moisture restrictions and irrigation requirements that could make energy crops non-competitive.

Any concave von-Neumann Morgenstern utility function can be used to study farmers risk aversion. I use power utility function characterized by constant relative risk aversion (CRRA). The power utility function uses one coefficient (CRRA) which reflects farmers' risk aversion level. It is computed using average economic returns from major crops such as corn, wheat, and soybeans at state level as following:[23] the net returns over variable costs per acre ($/acre) were computed for corn and soybeans for each state during 1980-2009. The historic economic returns were used to derive the cumulative distributions of corn and soybeans returns. The CRRA coefficient is estimated based on the intersection point(s) of these cumulative distributions. McCarl, et al. (1987) suggested that, the farmers prefer one major crop (corn or soybeans, in this case) to either side of the intersection point. Hence, at the point of intersection, the farmers would be indifferent between the returns from either crop. They developed a procedure that translates this point of intersection into a RAC metric. Hardaker, et al. (2004a) implemented this procedure for spreadsheet applications. I used this procedure for every state to compute a CRRA metric. Using this CRRA metric with the power utility function provides a way to model the impacts of farmers' risk aversion.

Hardaker, et al. (2004a) also demonstrated how to use such aggregate utility functions to calculate certainty equivalent (CE) values. The CE value can be defined as the guaranteed payoff that makes the average farmer indifferent between a guaranteed payoff from energy crops (through contracts) and a higher but uncertain payoff from field crops. The CE values are derived through a monotonic transformation of NPV. I used the aggregate power utility functions as

[23] The average economic returns for corn, soybeans and wheat are estimated at state level. This measure varies with the state thus enabling a way to compare multiple states.

described above to compute CE values. Hardaker et al. (2004a) showed that CE values can be used to rank different enterprises based on the risk aversion levels of farmers (CRRA).[24] Note that the CE values are derived based on average returns for a farmer in every state – hence, they are to be taken as evaluating the preferences of a representative farmer within a state.

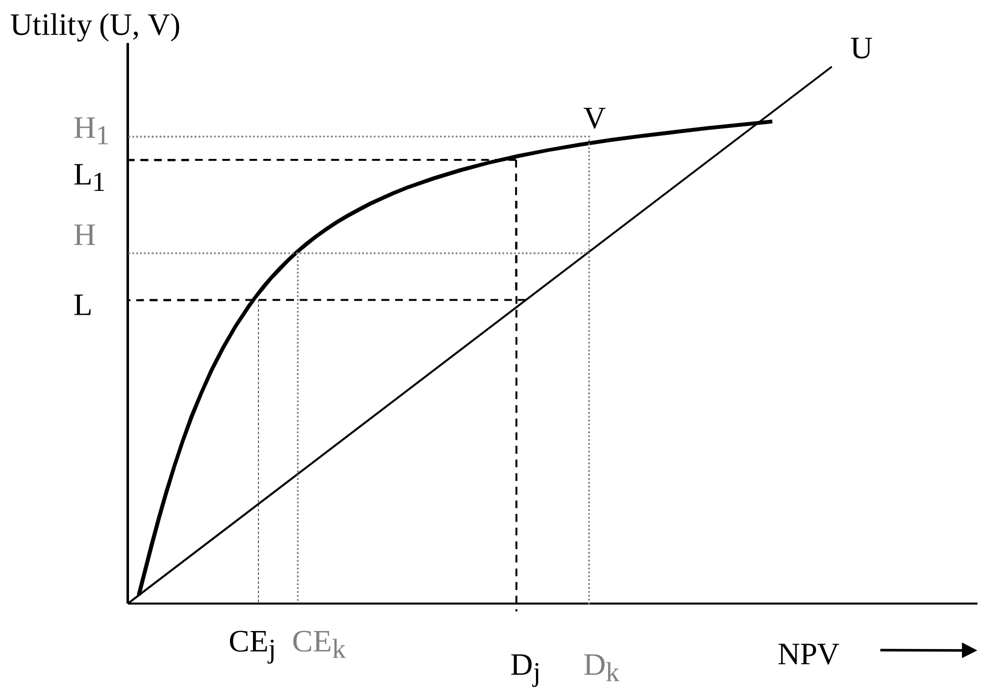
Comparison of NPV values for risk-neutral farmers

For risk neutral farmers, the von Neumann – Morgenstern utility function is linear (line U in figure 3.7). This leads to a linear correspondence between farmer's utility and NPV_i. Let the field crops have an expected NPV of D_j with utility L and energy crops have an expected NPV of D_k with utility H. The change in utility from converting lands from field crops to energy crops is represented by (H-L or $A_1 = D_k - D_j$). The empirical distribution for NPV can be used to derive an additional probability metric which measures the probability of getting higher NPV from energy crops compared to that of field crops (D_k), in notation, $\Pr(D_k > D_j) = \Pr(A_1 \geq 0)$. The calculation of $\Pr(A_1 \geq 0)$ is relatively straightforward. The cumulative distribution function (CDF) is derived for variable A_1. The proportion of area corresponding to the positive (or non-negative) values of A_1 gives the probability measure $\Pr(A_1 \geq 0)$. It is analogous to computing

[24] Only the risks associated with agricultural energy input price risks are modeled here; other risks related to crop yields, financial or institutional risks are not included.

the probability that energy crop's NPV_j has first degree stochastic dominance (FDSD) over field crop NPV_k or other land uses (Hansen, et al., 1978).[25]

Figure 3.7: Relationship between NPV and Utility for risk-neutral and risk-averse farmers



Comparison of CE values for risk-averse farmers

For risk averse farmers, the correspondence between NPV and utility is non-linear as depicted by the concave function V in figure 3.7 (Chibnik, 1981; Collins and Gbur, 1991; Lai, et al., 2003; Myers, 1989; Pei, et al., 2005; Ramaratnam, et al., 1986). When the risk-averse farmer shifts land from field crops (expected NPV D_j and utility H_1) to energy crops (expected value of

[25] For two revenue variables NPV_j and NPV_k with cumulative distribution functions $F(NPV_j)$ and $G(NPV_k)$, respectively, returns from crop j (NPV_j) stochastically dominates the other in first degree if $G(NPV_k) \geq F(NPV_j)$, with at least one strict inequality for some value of NPV.

D_k and utility L_1), the utility changes from H_1 to L_1. At the NPV level of D_j, the certainty equivalent value for a risk averse farmer is CE_j; similarly, at the NPV level of D_k, the certainty equivalent value for a risk averse farmer is CE_k. Hence, the change in utility for risk averse farmers ($H_1 - L_1$) can be expressed in terms of difference in CE values: $B_2 = CE_k - CE_j$. The advantage of using CE (and B_2) metric is that it can be interpreted in monetary terms. The probability that CE_k of energy crops exceeds CE_j of field crops, $Pr(CE_k > CE_j)$ is derived from the cumulative distribution for B_2, i.e. $Pr(B_2 > 0)$. The simulation software (@risk) is used to calculate the probability measures explained above.

Calculation of CE values in numerical terms is based on the concept of Stochastic Efficiency with Respect to a Function (SERF; Hardaker, et al., 2004a; Richardson, 2004; Richardson, et al., 2004). I use *power utility function* to model the risk-averse behavior of farmers. Power utility functions are commonly used to describe risk averse preference of economic agents at a macro (state or aggregate) level (Pindyck, 1986; Saltari and Ticchi, 2007).[26] The power utility function also has the desirable property of decreasing absolute risk aversion and constant relative risk aversion (CRRA). The CRRA measure reflects a constant level of risk aversion which is plausible at an aggregate state level (Meyer and Robison, 1991;

[26] Alternative approaches to eliciting individual farmer risk preferences would be surveys that directly compares the returns of energy crops and field crops – see Jensen et. al. (2005) for a similar study that focused on Tennessee farmers; such an approach may require considerable resources to contact farmers in different states

Popp, et al., 2005).[27] The power utility function also has the benefit of yielding a good fit to the data in many domains and is characterized by homotheticity (Danyang, 2002; Wakker, 2008).[28] The procedure to estimate CRRA (ρ) at state level is explained in appendix F.

The estimated CRRA value is substituted into the following power utility function expression $V(NPV) = [1/(1-\rho)] * NPV^{(1-\rho)}$, where V(NPV) is the power utility function of risk averse farmers. The empirical distribution of NPV is used to derive an empirical distribution for the utility function, V(NPV). Let the mean value of the empirical distribution of V(NPV) be denoted by $V^{\#}(NPV)$. Then the utility function is inverted to obtain the certainty equivalent value as $CE = (1-\rho) * [V^{\#}(NPV)]^{1/(1-\rho)}$.

3.5 Results and Discussion

A sample budget generated for corn and miscanthus crops in Nebraska for the year 2013, i.e. 4th year in a 10-year rotation, is given in the following table 3.9a. Similar budgets were forecast for all field crops and energy crops corresponding to years 2010-2019. In 2013, the yield of corn could be expected to average 122.5 bushels/acre in Nebraska. The net economic returns for corn was calculated at $ 153.58, 286.56 and 428.33 per acre for low, reference and high crude oil price scenarios respectively. The yield of miscanthus would be 9.9 tons/acre with net returns

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[27] Aggregate risk aversion at the level of state or multiple counties – since 'a group' of farmers in that region have to plant energy crops if energy crops were to become a major feedstock for cellulosic ethanol production in that region. The finest resolution of data for costs of production and commodity prices are available only at state level (rather than county level or farm level); an implicit assumption here is that farmers are considered to be homogeneous within a state.

[28] Homotheticity: Multiplication of the same constant σ (> 0) with NPV of either enterprise do not change the preferential order derived based on CE values, among alternative enterprises

of $-180.38, 331.44 and 1043.57 per acre under those three scenarios. The returns from one year are not sufficient to compute the overall change in farmers' income due to shifting to energy crops. Hence, similar budgets were created for all years during 2010-2019, and used to compute an estimate of NPV for energy crops and field crops. The NPV estimates for Nebraska corn/soybean-miscanthus comparison are given in table 3.9b. The average NPV values differ with every scenario. Energy crop NPV is less than that of corn when crude oil prices are low (scenario I), comparable under reference case (scenario II) and higher than that of corn crop when crude oil prices are high (scenario III). The direct implication of these results is that high yielding energy crops (miscanthus) can be expected to compete with field crops if crude oil prices stay high in the next 10 years. Since, crude oil prices fluctuate, NPV values also fluctuate resulting in an empirical distribution for NPV.

Table 3.9a: Model Budget for corn and miscanthus crops in Nebraska (Year 4)

	Crude oil price scenario		
	Low economic growth	**Reference case**	**High economic growth**
Expected Crude oil price in 2013 ($/barrel)	49.20	81.00	128.90
Field crop: Corn			
Yield in 2013 (bu/ac)	122.50	122.50	122.50
Projected price ($/bushel)	3.14	4.20	5.64
Production costs ($/ac)			
Energy input costs			
Diesel	6.82	9.29	12.73
N fertilizer	30.86	37.91	46.95
P fertilizer	3.25	8.56	13.61
K fertilizer	-	-	-
Non energy input costs	117.19	117.19	117.19
Fixed costs			
Land rent	66.71	66.71	66.71
Labor	5.72	5.72	5.72
Net returns for 2013 ($/ac)	**153.58**	**268.56**	**428.33**
Energy crop: Miscanthus			
Yield (ton/ac)	9.93	9.93	9.93
Residual value ($/ton)	24.40	78.58	153.88*
Production costs ($/ac)			
Energy input costs			
Diesel	49.93	68.03	93.17
N fertilizer	35.39	43.47	53.84
P fertilizer	-	-	-
K fertilizer	-	-	-
Non energy input costs	235.65	235.65	235.65
Fixed costs			
Land rent	66.71	66.71	66.71
Labor	35.00	35.00	35.00
Net returns for 2013 ($/ac)	**-180.38**	**331.44**	**1043.57***

* the values are very high due to very high residual value that could be paid for energy crop biomass under higher crude oil prices; the actual prices paid by the biorefinery will be less than these residual values. Also note that miscanthus yield

levels are very high in Nebraska making it highly profitable if there is demand for miscanthus biomass.

Table 3.9b: NPV values of corn and miscanthus crop for Nebraska (2010-2019)

	Crude oil price scenario		
NPV value	**Low**	**Reference case**	**High**
Corn-Soybean rotation	$ 1538	$ 2547	$ 3949
Miscanthus crop	- $ 1839	$ 2096	$ 7587

Miscanthus and corn-soybean (CS) rotation

The following results are derived based on the empirical distributions of NPV for risk neutral farmers based on 1000 simulations for every state. The break-even prices required for miscanthus to compete with CS rotation – to cover energy crop production costs and the opportunity costs (lost profits) – are given in figure 3.8. The three figures correspond to three high, reference case and low crude oil price scenarios. The subsidies required for cellulosic biomass are summarized in figure 3.9. If the break-even price was more than the residual value of biomass (biofuel revenues minus processing costs), then subsidies for cellulosic biomass are required as required in low crude oil price scenario. But if the residual value is more than the break-even price, then subsidies are not required as can be seen in high crude oil price scenario. The probability of biomass residual value exceeding the break-even price (corresponding to CS rotation) is given in figure 3.10.[29] Figures 3.8, 3.9 and 3.10 correspond to planting miscanthus in fields that are traditionally planted with corn and soybeans in yearly rotation.

When crude oil prices are low, the break even prices required for miscanthus range from $27-71/ton. The residual value of energy crop biomass in the corresponding low crude oil price scenario was estimated at $22 per ton. Since the break even prices are higher than the residual

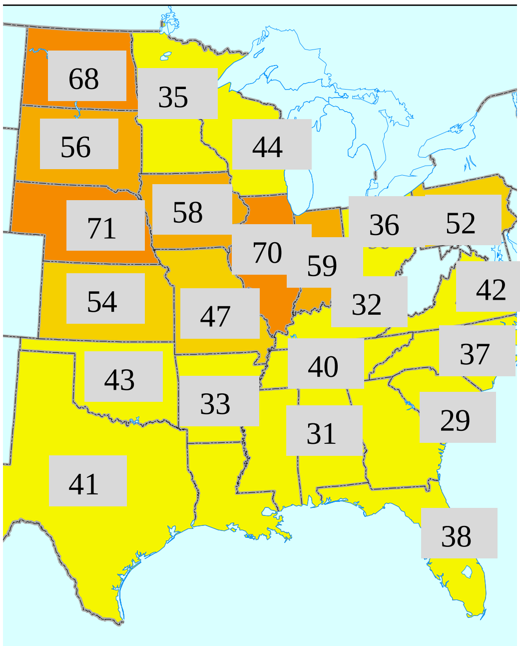
[29] Similar tables are available for other field crops (cotton, wheat) and other energy crop switchgrass. Only the results comparing miscanthus with corn are discussed here.

value of biomass, additional subsidy support is needed to convert lands from corn-soybean rotation to energy crops (miscanthus in this case). In the absence of subsidy support over the entire 10 year time frame, it will not be economical to divert corn-soybean fields to miscanthus production in low crude oil price scenario because it leads to a reduction of expected NPV. Hence farmers would not convert their lands from field crops to energy crops when crude oil prices are low. To illustrate, the break-even price for miscanthus in Alabama is $31/ton. Only $22/ton would be covered by the residual value. Hence, a subsidy of $9/ton is required for Alabama (figure 3.9). The subsidy of $9/ton for Alabama is required for all biomass produced during 2010-2019.[30] That is, if 84 tons of miscanthus were produced per acre over a 10 year time-period, then the total amount of subsidy required would be $9/ton * 84 tons = $756 per acre over 10 years. Such large amounts of required subsidies indicate that energy crops are uncompetitive against corn-soybeans rotation when crude oil prices are low. The results derived from the empirical distributions on the probability of receiving higher returns from miscanthus also reflect the same result (figure 3.10). Compared to miscanthus, switchgrass yields would be even lower leading to higher break even prices and requiring more subsidies. Hence, conversion of corn-soybean cropland to switchgrass (or any other energy crop with similar yield potential) is much more unlikely when crude oil prices are low. The amount of subsidies reported above is very sensitive to processing costs. When processing costs are assumed to increase from the target rate of $1/gallon to the current levels of $1.50/gallon, the required subsidies are found to increase substantially.

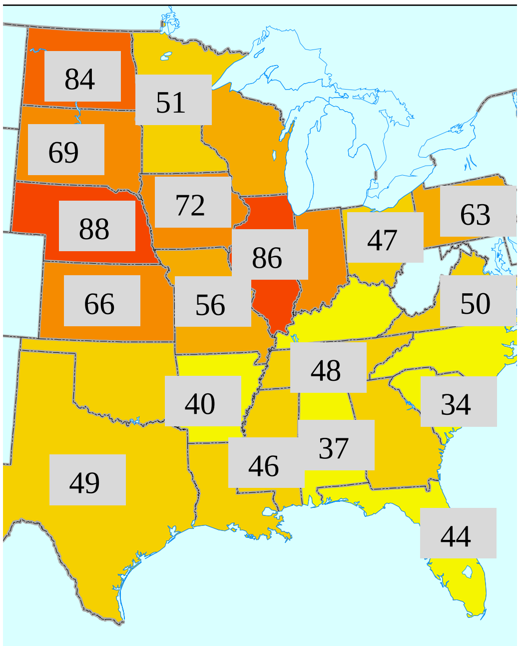
[30] There is a federal subsidy of $45/ton under USDA-BCAP program for all biomass including energy crops during the first two years of planting (USDA, 2010).

Figure 3.8: Break even prices for miscanthus replacing corn-soybean rotation ($/ton) [31]

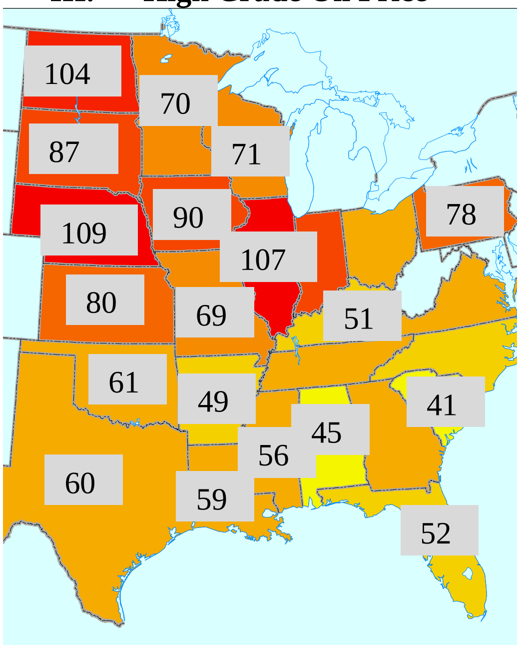
I. Low Crude Oil Price



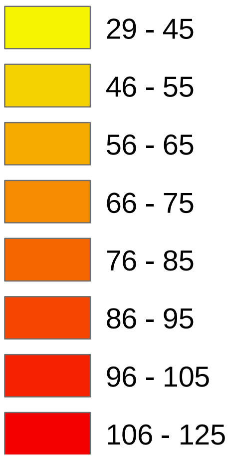
II. Reference Case



III. High Crude Oil Price



Legend



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[31] Figures 3.8, 3.9 and 3.10 compare the competitiveness of miscanthus against that of corn-soybeans rotation

Figure 3.9: Subsidy required for miscanthus replacing corn-soybean rotation ($/ton)

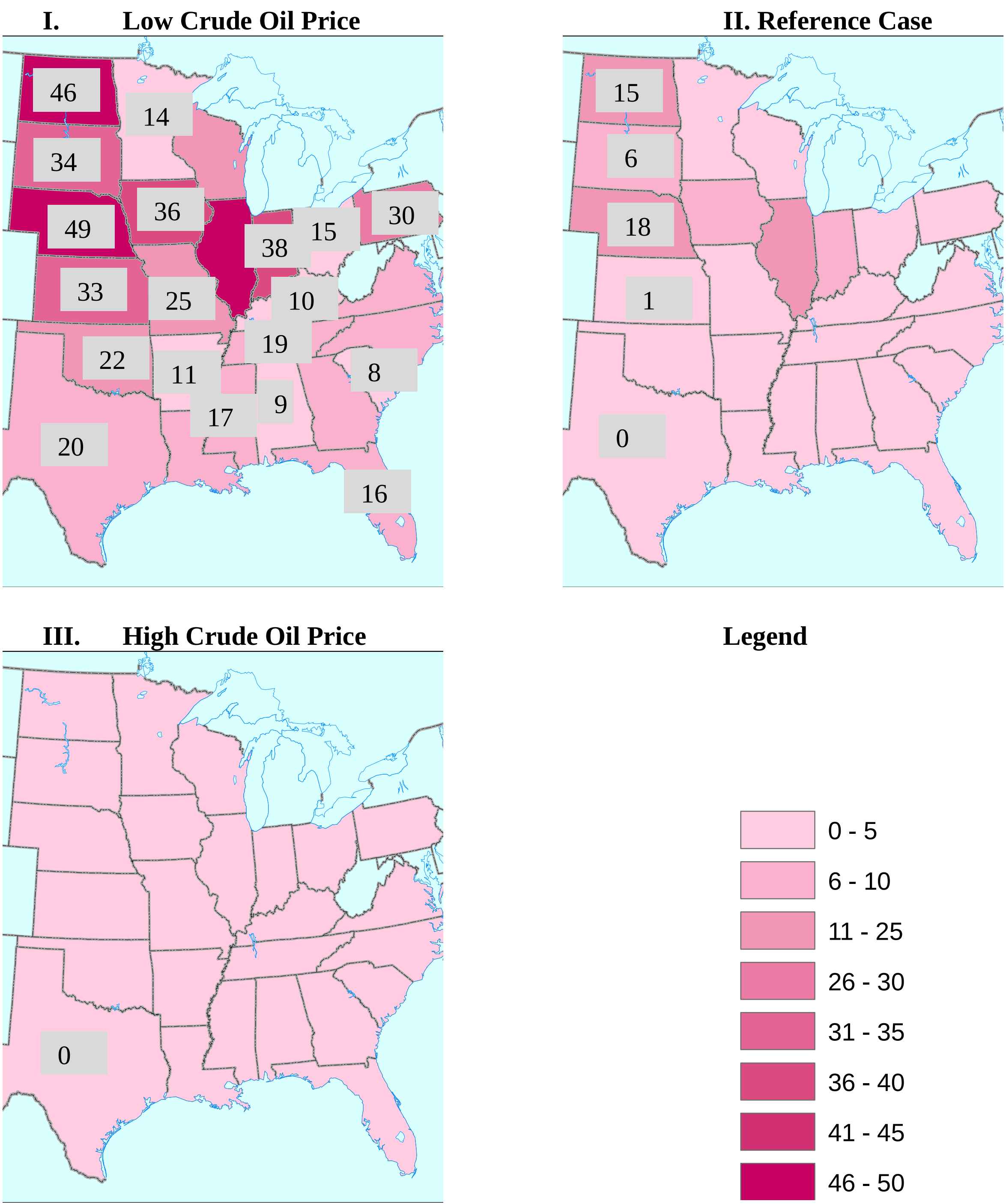
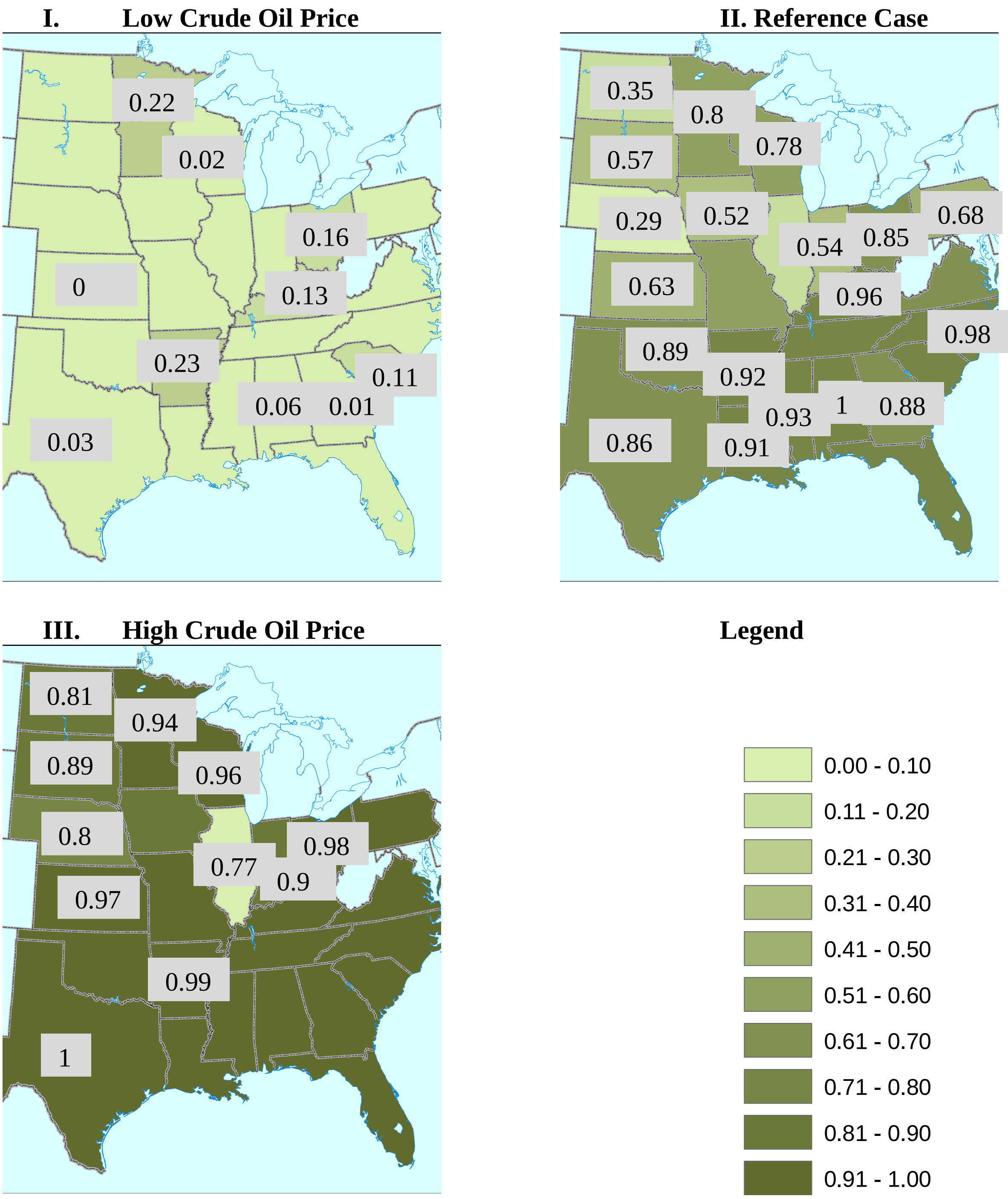


Figure 3.10: Probability that cellulosic biomass subsidies are not required for miscanthus replacing corn-soybean rotation (percentage)



In reference case scenario (II), the state level analysis suggest that miscanthus is competitive with CS rotation in the states Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee and Virginia. When the crude oil prices fluctuate in the range of $49-113 per barrel in scenario II, the break even prices for miscanthus increase by 17% to 45% compared to scenario I. The reasons for an increase in break-even prices are two-fold: (i) higher miscanthus production costs due to higher agricultural input costs and (ii) higher opportunity costs associated with higher profits that were lost with replacing corn-soybeans rotation with miscanthus. In scenario II, there is no need for cellulosic biomass subsidies because the break even prices are lower than residual value estimated at $70/ton (except the Midwestern states). The high probability estimates (figure 3.10) shows that the economic returns are consistently higher with miscanthus. The reasons for better consistency are two-fold: (i) the residual value of cellulosic biomass is higher in the reference crude oil price scenario which consistently increased the returns from energy crops; (ii) while the NPV for miscanthus and corn–soybeans increased in scenario II compared to scenario I, the increase in the former is much higher than for the latter; i.e. the opportunity cost of planting miscanthus and replacing corn-soybean crops declined. In scenario III (crude oil prices ranged from $88-178/barrel), miscanthus is found to be attractive in all states including the Midwestern corn-soybean belt. The residual value available to pay for cellulosic biomass is above $150/ton eliminating the need for any cellulosic biomass subsidies. That is, energy crop cultivation would be very competitive with corn-soybeans rotation when the crude oil prices stay high over the 10 year duration, 2010-2019.

Miscanthus and other crops

Table 3.10 presents a comparison of miscanthus with other major crops such as wheat, sorghum, and cotton or land uses such as pasture for selected states. The pattern of results is similar to those discussed above. The major difference is with the specific

Table 3.10: Break-even price for miscanthus ($/ton) – selected crops, selected states#

State	Crop	Crude oil price scenario		
		I. Low*	II. Reference case	III. High
Indiana	Corn-soybeans	59 (37)	72	87
Missouri	Wheat	42 (20)	50	59
Texas	Cotton	41 (19)	48	56
Kansas	Sorghum	49 (27)	59	69
Tennessee	Pasture	32 (10)	35	38

* The amount of subsidies required (given in the parenthesis) is calculated as Max[0, Break-even price – residual value ($22/ton in low crude oil price scenario)]. Under the assumption of $1/gallon processing costs, subsidies are not required for reference case and high crude oil price scenario.
# More results on break-even prices for miscanthus when planted in place of other crops are given in Appendix G

values estimated for break-even prices of miscanthus. Since wheat, cotton and sorghum crops are less profitable than corn and soybeans, the break-even prices are lower. This also reduces the amount of required subsidies. These results show that the competitiveness of energy crops is heavily dependent on the type of land that is planted with miscanthus and the type of crop that is replaced.

The energy crops would be more competitive in pasture lands or other marginal lands such as Conservation Reserve Program (CRP) land, because of low economic returns from pasturelands. Although field crop productivity is low in pasture or marginal lands, pastures are more suitable to grow herbaceous grasses such as miscanthus. The low land opportunity cost of diverting them to energy crop production is another reason that contributes to low break-even price for miscanthus and low subsidies. These results for other states were found to follow the same pattern and remain consistent with all crops in other states and not presented here. The probability of getting higher economic returns increased substantially in crude oil price scenarios II and III.

Impact of risk aversion

For risk-averse farmers, the comparison of NPV values is replaced with a comparison of certainty equivalent values. Even when the farmers are modeled as risk averse, the economic returns from miscanthus compare favorably with field crop returns when crude oil prices are high. The results remain the same in terms of geographic suitability and economic viability in all three scenarios. The risk-averse farmers would view energy crops less favorably (favorably) when the crude oil prices are low (high). The major difference is in value of probability estimate. Due to greater dependence on fossil fuel inputs for field crop production, the fluctuations in crude oil prices translate into higher fluctuations in the NPV values of corn-soybeans returns. This reduces the certainty equivalent value derived from corn-soybeans which in turn increases the probability of receiving higher returns from energy crops for risk-averse farmers. The results are not very different for risk neutral (NPV) and risk-averse (CE) farmers because the estimated constant relative risk aversion coefficients (CRRA) are relatively low. CRRA estimates can range from zero to infinity. The break-even risk aversion coefficient procedure following in this study gave CRRA estimates in the range of 0.99-1.003. This range corresponds to lower end of risk aversion. Hence, the impacts of risk can be expected to be low at the aggregate (state) level.

3.6 Conclusions

The potential for dedicated herbaceous energy grass crops such as miscanthus, and switchgrass is less certain because they are yet to be grown in large scale. The demand for energy crops and the economics of energy crops are affected by crude oil prices. To evaluate the role of crude oil prices, a multi-state study was conducted over a 10 year 2010-2019 time frame. First, crude oil prices were simulated using EIA estimates and a weighted average of historical and implied price volatility of crude oil prices. The cost of energy inputs (diesel, fertilizers NPK), prices for agricultural outputs (corn, soybeans, wheat, sorghum, cotton) were derived based on the simulated crude oil price. The yield of field crops were projected using the historical trend levels. Similarly, the crop production budgets for energy crops (miscanthus and switchgrass) were generated for the years 2010-2019. The energy crop input costs and output prices were derived based on crude oil prices; the energy crop yields were derived based on the state level temperature and precipitation data. The repeated simulation of budgets over 1000 iterations enabled estimation of empirical distribution for the NPV values for field crops and energy crops. The NPV values for field crops and energy crops were compared to model the decision of risk neutral farmers. The NPV values were monotonically transformed to derive certainty equivalent (CE) values for modeling risk averse farmer decisions. The CE values were derived by assuming a power utility function characterized by constant relative risk aversion (CRRA). The CRRAs were derived for each state using SERF procedure described in Hardaker et al (2004).

The results suggested that for energy crops to be competitive with existing land uses, the crude oil prices would have to be high over the period 2010-19. The probability of getting higher economic returns from energy crops such as miscanthus increased substantially when crude oil prices, biofuel and cellulosic biomass prices were high. In particular, the southeastern states such as Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee and Virginia would be more suitable for energy crop cultivation due to higher yields and higher economic returns. Cellulosic biomass subsidies for energy crops would be required only when crude oil prices remained low. The amount of subsidies estimated for energy crops was found to be sensitive to biofuel processing cost assumption Switchgrass might not become a major cellulosic feedstock unless its yield levels are comparable to that of miscanthus or other high yielding energy crops. The above results derived for a risk neutral farmer by comparing NPV values remained relatively similar for risk averse farmers as well. The low level of risk aversion level at the aggregate (state) level was the main reason for lack of differences between risk neutral and risk averse farmers. The key determinants of energy crop competitiveness were found to be the yield potential of energy crop which depends on the regional climatic differences, and the residual value of cellulosic biomass that depends on crude oil prices, processing and transport costs. This study confirms that subsidies for energy crops are required when the crude oil prices are low. That is, the subsidies have to be counter-cyclical to crude oil price movements. This is markedly different from the proposed Biomass Crop Assistance Program (BCAP) which pays matching subsidies where the subsidies are equal to the payment received from the biomass processing facility. Under the BCAP program, the subsidies will be higher when the crude oil prices are higher because the latter increases the ability to pay more for energy crops. The results of this study suggest an alternative way to administer the biomass subsidy program.

3.7 APPENDICES

Appendix A Real options value

I account for the important factors that cause uncertainty in energy crop returns: crude oil prices, and climatic parameters. In addition to crude oil price fluctuations, farmers face other types of uncertainties that may add or reduce value and affect their utility derived from planting energy crops. One of the most common forms of additional economic value emerge from the ability to delay energy crop planting till a later date (Dixit and Pindyck, 1994; Price and Wetzstein, 1999; Song, et al., 2009). Other sources of uncertainties that affect energy crop planting include (i) delay in energy crop adoption in wait of better energy crop varieties, (ii) delay in energy crop adoption in search of more information about local markets for energy crops and prices (which implicitly depends on crude oil prices), (iii) uncertainty due to public policy changes that affect monies (prices and subsidies) available for energy crop biomass and cellulosic biofuels, (iv) lack of perspectives on preferred feedstock or technology for cellulosic biofuel production, and (v) unknown demand for the yet-to-be planted energy crops.[32] All these factors delay immediate planting of energy crops due to inherent economic value (termed as real options value – see criterion D in table 3.2). I exclude these factors for the following reasons:

(a) The uncertainties such as 'information on preferred feedstock, demand for feedstock, better seed varieties,' are faced equally by all farmers in all states. Hence, the economic value arising with delaying the adoption of energy crops is likely to be similar for farmers across the US states. In other words, the real option value arising from these factors will not be the distinguishing factor across the states. In fact, the farmers will not grow energy crops if there is no biorefinery within a 50-100 mile radius, because there will be no demand for energy crop biomass. This study is applicable to cases where biorefinery is planned creating sufficient

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[32] Agricultural lands can be converted from energy crop plantations to field crop production as already seen with returning CRP lands into row crop production. Although such a conversion potentially incurs high costs of land reclamation, the farmers would require a higher price for energy crop biomass rather than delay planting of energy crops to avoid land irreversibility.

demand for cellulosic biomass for biofuel production purposes. Alternatively, if energy crop production is competitive in a location, it will reduce the constraints faced by the biorefinery with regard to sourcing biomass feedstocks.

(b) The farmers do not delay energy crop planting when there is demand for energy crops resulting in higher prices for energy crops or higher residual value after accounting for biofuel processing costs. The farmers subscribed to growing switchgrass in Tennessee pilot project, and in Charitan Valley Biomass Project in Iowa because the markets and prices were assured. Switchgrass planting was immediate in both cases when the farmers have assured contracts for energy crops – hence, the main question remains what prices and revenues would farmers require as part of the contract to plant energy crops instead of existing land uses.

(c) If the biorefineries consider energy crops as the preferred feedstocks, then biorefineries would promote planting of energy crops. Biorefineries would rather not delay planting of energy crops because energy crops require an establishment period of 1-2 years before achieving maximum yield potential. Hence, biorefineries have incentives to reduce the value arising due to additional real options value to secure cellulosic biomass for biorefinery operations. In fact, the farmers who sign up first would be the preferred suppliers since those farmers help reduce uncertainty faced by the biorefinery. This study is applicable to evaluating energy crop competitiveness when there is sufficient demand for biomass. The results from this study can help decide whether to locate a biorefinery, that prefers energy crop biomass, in a particular geographic region or not.

(d) Crude oil price fluctuations affect the ability to construct a biorefinery and create demand for energy crop biomass. The uncertainties faced in the construction of biorefineries are much bigger than the uncertainties faced by the farmers in growing energy crops. The results from this analysis are applicable when a biorefinery has been decided in a location removing the uncertainties described above.

e) Long term contracts are needed to procure entire biomass produced from energy crop fields. These long term contracts will include terms of farm production support to farmers in establishing, and growing energy crops immediately (Kumarappan and Gustafson, 2009). That is, the contract terms will be designed to reduce market uncertainties and promote planting of energy crops immediately once the biorefinery is located in the vicinity. These contract terms essentially function to diminish the real options value in delaying the planting of energy crops by farmers. Although individual efforts of biorefineries to encourage farmers plant energy crops would vary with the location and management, all biorefineries will have to provide comparable incentives. This study evaluates those incentives in terms of break-even prices, subsidies and probability of receiving higher returns from energy crops. A simulation study that derives an empirical distribution of NPV for energy crops is an useful analysis – this is the focus of my research. Due to the above reasons, the real options value to delay energy crop planting is deemed low and excluded from this study.

Appendix B Forecasting Historical Volatility

Step 1: Calculation of weights (based on 1993-2009 data)[33] (Granger and Ramanathan, 1984):

$\omega_0^\wedge$, $\omega_1^\wedge$, $\omega_2^\wedge$ are the estimated weights (regression coefficient estimates) derived from the regression $r_t = \omega_0 + \omega_1\ IV_p + \omega_2\ HV_p + \varepsilon$, where

r_t is the spot price volatility estimate calculated as $\ln(S_t/S_{t-1})^2$ using daily data for years 1993 – 2009

S_t is the spot market price of crude oil at time t

IV_p is the past data on implied volatility (based on options on futures) for years 1993 – 2009

HV_p is the past data on historical volatility (based on futures contracts) for years 1993 – 2009

ε is the error term ~ N(0,1)

Step 2: Forecast of crude oil price volatility (for years 2010-2019)

$$SV_y = \omega_0^\wedge + \omega_1^\wedge\ IV_f + \omega_2^\wedge\ HV_f, \text{ where}$$

SV_y is the weighted volatility forecast for every year y = 2010…2019 (t = 1, 2, …10)

IV_f is the implied volatility forecast (using IV_p) for years 2010 – 2019[34]

HV_f is the historical volatility forecast (using HV_p) for years 2010 – 2019[35]

The series IV_p and HV_p are available from Commodity Research Bureau, CRB (2009). These two series IV_p and HV_p are used to forecast future values (IV_f and HV_f) for years 2010-2019 using GARCH type models.

Forecasting historical volatility (HV_f):

I use HV_p estimates provided by CRB (2009) to forecast HV_f. Similar to IV_p series, the historical volatility data series (HV_p) is assembled by averaging daily estimates corresponding to

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33 Data on historic volatility is available from 1993 – hence that is the reason for the starting year in 1993.

34 For years 2016 through 2018, less number of options are traded in NYMEX. Hence, the 2015 value for implied volatility will be multiplied by $\sqrt{T}$, where T = 2 for year 2016, 3 for year 2017 and so on.

35 Among GARCH models, single equation GARCH(1,1) model is found to be better predictor of historical volatility than other GARCH models (see Padorsky, 2006)

crude oil futures contracts. To illustrate, consider the crude oil futures contract that would expire in September 1995. This contract would have been actively traded on a daily basis during the months of September 1994 – August 1995. Thus, there are about 250 estimates of HV_p for the futures contract expiring in September 1995. A single historical volatility estimate for the September 1995 contract is derived as an equally weighted average of all those 250 estimates. Using equally weighted averages ensures consistency with the procedure used for assembling the dataset on IV_p. This procedure was repeated for all months during the years 1989-2009 to assemble the monthly time series data for HV_p. This series is fitted with an ARMA-GARCH model to forecast HV_f.

Based on the correlogram, and information criteria (AIC), an ARMA(3,1) was found to account for autocorrelation in HV_p. An ARMA(3,1)-GARCH(1,1) model was chosen to forecast HV_f. To account for the fact that crude oil price volatility is heteroskedastic (see figure 3.5), I included crude oil prices as an exogenous regressor in the ARMA-GARCH estimation. I compared two GARCH models where crude oil prices entered only the mean equation or only the variance equation as a regressor. Using crude oil price as a regressor in the **mean** equation yielded normally distributed errors (*Null Hypothesis*: Normally distributed errors; Jarque Bera statistic = 2.778483 with a p-value of 0.2492) – this overcomes the problem noted by Agnolucci (2009) that the residual error terms were not normally distributed for any of the GARCH type models fitted for crude oil price volatility. The forecast HV_f values are presented in figure 3.5. Since the projections are made using monthly data, there are 12 volatility estimates for every year during 2010-19. I compute a simple average of first 12 observations and use it as the projected HV_f estimate for 2010; the forecast observations numbered 13 to 24 are used to derive the HV_f forecast for year 2011 and so on.

Appendix C Forecasting implied volatility

The IV data for the years 1993-2015 (only a few selected months for the years 2010-2015) is available from Commodity Research Bureau (CRB, 2009, 2009b).[36] The daily IV estimate for a contract is computed using eight call and put options on crude oil price futures contracts:

two call options that are just in-the-money;

two call options that are just out-of-the-money;

two put options that are just in-the-money and

two put options that are just out-of-the-money.

There are many advantages to using only the contracts that are just in or out-of-the-money contracts (in other words, nearest to the money contracts): they are found to be the least biased when volatility is time-varying; using only the nearest to the money options provides implied volatility forecast estimates that are robust to non-normal errors; and nearest to the money options yield estimates that are least affected by non-simultaneity (Corrado and Miller, 1996; Fleming, et al., 1995); also see footnote 1 in Agnolucci (2009).

Since options contracts are traded daily till expiry, options contract for every month has daily estimates of implied volatility expressed in annualized terms. I derive one representative estimate from this time series data. For example, the options contract expiring in June 2011 is actively traded during the prior 30 months (2008-2011 for this example). There are approximately 660 daily observations (22 days per month * 30 months = 660 daily observations) for June 2011 alone the options contract was traded. I compute the equally weighted mean of these estimates and use it as the volatility estimate for June 2011. I adjust the time to expiry to

[36] Options on crude oil futures are actively traded for 4 to 5 years (2010-2015). Beyond that, they are less liquid and those options do not provide much information on future implied volatility

compute the equally weighted mean values (Hull, 2006). Uniformly weighted measures are found to be the least biased estimates compared to other weighting procedures (Corrado and Miller, 1996; Ederington and Guan, 2002). This procedure is repeated for all months between January 1993 and December 2012. Since there are no estimates of IV_f for the months during 2013-2019, I use ARMA-GARCH model to project IV_p (table 3.6). The forecast values are in monthly terms; since I need only annual estimates of IV_f, I compute non-overlapping average of IV_f estimates from January till December for the years 2013-2019.

Appendix D Temperature (GDD) and Precipitation Values

GDD and precipitation values in various states are given in tables 3.D1 and 3.D2, respectively. Both GDD and precipitation vary across states affecting energy crop yields. Even within a state, they vary over time. These intra-state variations are captured using a uniform distribution. The simulated values of temperature and precipitation are plugged into equations in table 3.5 with minimum and maximum values. To illustrate a representative energy crop yield calculation, consider the state of Alabama: the average GDD is 5535, precipitation is 57.3 inches resulting in switchgrass yield of $2.2 + 0.02 * 5535 * 57.3/1000 = 8.5$ tons per acre per year and miscanthus yield of $6.6+0.04 * 5535 * 57.3/1000 = 19.3$ tons per acre per year.

Table 3.D1: Growing Degree Days in US states

FIPS	State	Min	Average	Median	Max
1	Alabama	4,978	5,535	5,671	5,914
5	Arkansas	4,334	4,995	5,224	5,363
4	Arizona	2,804	4,861	4,747	7,381
6	California	1,163	4,333	4,515	6,861
8	Colorado	2,451	3,185	3,228	4,019
9	Connecticut	3,321	3,381	3,381	3,441
10	Delaware	3,921	3,967	3,967	4,012
12	Florida	5,998	6,836	6,770	8,122
13	Georgia	5,044	5,599	5,678	5,977
19	Iowa	2,862	3,193	3,182	3,702
16	Idaho	2,345	2,830	2,675	3,347
17	Illinois	3,287	3,628	3,633	4,066
18	Indiana	3,229	3,658	3,621	4,291
20	Kansas	3,528	4,083	4,133	4,488
21	Kentucky	4,030	4,406	4,514	4,639
22	Louisiana	5,726	6,155	6,319	6,463
25	Massachusetts	2,706	2,903	2,845	3,159
24	Maryland	3,858	3,911	3,911	3,963
23	Maine	1,903	2,215	2,238	2,524
26	Michigan	1,724	2,543	2,548	3,259
27	Minnesota	1,723	2,370	2,387	3,082
29	Missouri	3,358	3,962	3,942	4,570
28	Mississippi	5,125	5,651	5,655	6,315
30	Montana	1,846	2,378	2,387	2,887
37	North Carolina	3,805	4,739	4,714	5,335
38	North Dakota	2,172	2,432	2,441	2,684
31	Nebraska	3,028	3,332	3,243	3,792
33	New Hampshire	290	1,531	1,531	2,771
34	New Jersey	3,879	3,889	3,889	3,899
35	New Mexico	3,358	4,453	4,574	5,316
32	Nevada	2,795	3,773	3,599	6,592
36	New York	2,518	2,933	2,933	3,436
39	Ohio	3,004	3,423	3,419	3,868
40	Oklahoma	4,695	4,985	5,054	5,179
41	Oregon	1,593	2,471	2,511	3,177
42	Pennsylvania	2,173	3,150	3,208	4,085
44	Rhode Island	3,344	3,344	3,344	3,344
45	South Carolina	4,929	5,417	5,356	5,902
46	South Dakota	2,469	2,750	2,749	3,098

Table 3.D1 (Continued)					
FIPS	**State**	**Min**	**Average**	**Median**	**Max**
47	Tennessee	3,916	4,656	4,771	5,356
48	Texas	4,253	5,952	5,979	7,504
49	Utah	2,768	3,258	3,350	3,550
51	Virginia	3,830	4,325	4,282	4,767
50	Vermont	2,382	2,554	2,554	2,725
53	Washington	1,067	2,312	2,406	3,199
55	Wisconsin	2,181	2,678	2,694	3,059
54	West Virginia	2,779	3,491	3,547	3,992
56	Wyoming	1,693	2,376	2,480	2,630

Source: (NOAA, 2009)

Table 3.D2: Precipitation in US states (in inches)

FIPS	State	Min	Average	Median	Max
1	Alabama	53.4	57.3	55.9	64.0
5	Arkansas	40.9	54.8	49.3	74.1
4	Arizona	3.2	10.7	8.0	22.8
6	California	-	15.0	13.2	37.0
8	Colorado	7.6	11.8	11.2	16.2
9	Connecticut	41.7	42.9	42.9	44.1
10	Delaware	40.8	40.8	40.8	40.8
12	Florida	39.6	52.8	51.8	65.7
13	Georgia	44.6	48.3	49.5	51.0
19	Iowa	25.9	32.8	33.4	38.4
16	Idaho	12.1	12.2	12.1	12.4
17	Illinois	-	30.4	36.0	39.1
18	Indiana	34.8	39.2	39.5	43.1
20	Kansas	18.2	26.6	28.8	35.2
21	Kentucky	44.4	47.0	46.9	49.7
22	Louisiana	46.1	55.9	57.9	61.9
25	Massachusetts	41.5	46.1	47.8	49.0
24	Maryland	40.8	40.8	40.8	40.8
23	Maine	36.6	40.5	40.5	44.3
26	Michigan	28.3	32.1	32.6	36.0
27	Minnesota	24.4	28.0	28.3	30.0
29	Missouri	37.5	39.3	38.3	43.0
28	Mississippi	55.4	56.0	55.9	56.7
30	Montana	11.0	13.8	14.3	16.5
37	North Carolina	41.4	48.5	47.6	56.1
38	North Dakota	13.7	16.2	15.5	19.5
31	Nebraska	15.3	23.8	25.0	29.9
33	New Hampshire	36.4	67.7	67.7	99.0
34	New Jersey	40.3	42.1	42.1	44.0
35	New Mexico	8.9	12.2	12.6	15.1
32	Nevada	4.1	8.0	8.2	10.1
36	New York	32.0	40.0	38.9	47.3
39	Ohio	33.0	36.9	36.8	39.7
40	Oklahoma	33.4	37.0	37.0	40.6
41	Oregon	10.0	33.5	36.0	66.4
42	Pennsylvania	36.2	39.9	40.6	43.5
44	Rhode Island	45.5	45.5	45.5	45.5
45	South Carolina	48.5	50.3	50.6	51.5
46	South Dakota	16.6	19.8	19.3	23.9

Table 3.D2 (Continued)					
FIPS	State	Min	Average	Median	Max
47	Tennessee	40.7	49.1	49.7	53.8
48	Texas	8.8	29.0	29.5	57.2
49	Utah	9.8	13.0	13.0	16.2
51	Virginia	39.9	41.9	41.1	44.6
50	Vermont	34.5	34.5	34.5	34.5
53	Washington	-	36.5	37.2	105.2
55	Wisconsin	28.8	30.8	30.7	32.9
54	West Virginia	41.0	42.5	42.0	44.8
56	Wyoming	12.5	13.6	13.7	14.5

Source: (Utah Weather Center, 2009)

Table 3.D3: Fixed costs of land in crop production in US states

	Land Rental Value ($/ac/year)			
State	Minimum	Average	Maximum	Compound Annual Growth Rate
AL	20	40	80	0.97%
AR	19	61	98	0.00%
AZ	32	172	236	2.78%
CA	13	342	369	
CO	5	24	33	
DE	28	67	122	
FL	21	39	82	2.59%
GA	26	45	96	-0.60%
IA	38	140	216	0.45%
ID	5	59	70	-0.07%
IL	37	140	213	0.43%
IN	32	118	183	0.83%
KS	15	41	70	2.21%
KY	22	81	125	0.97%
LA	19	68	106	-0.18%
MD	28	65	120	
MI	29	69	127	1.92%
MN	21	93	135	0.43%
MO	28	82	138	0.04%
MS	18	65	101	0.74%
MT	6	21	32	
NC	26	56	109	-2.26%
ND	12	42	65	-0.08%
NE	13	78	105	0.56%

Table 3.D3 (Continued)				
	Land Rental Value ($/ac/year)			
State	**Minimum**	**Average**	**Maximum**	**Compound Annual Growth Rate**
NJ	28	51	106	-2.46%
NM	2	43	47	
NV	6	43	54	
NY	28	42	97	-1.67%
OH	32	90	154	0.87%
OK	10	30	50	-3.44%
OR	15	107	138	
PA	28	48	105	0.95%
SC	21	31	74	-2.12%
SD	13	54	81	2.70%
TN	20	71	112	-0.68%
TX	9	24	42	-0.71%
UT	11	67	89	
VA	20	43	84	2.25%
WA	15	207	237	
WI	41	76	157	-1.56%
WV	22	31	76	-1.26%
WY	4	45	54	

Source: (USDA - NASS, 2007); the growth rates are computed only for major states in the eastern half of US which suit energy crop production (Graham, et al., 2007).

Appendix E List of State Extension Websites

Table 3.E1: List of state extension websites used to collect field crop production costs

State	State Extension Budget link
Alabama	http://www.ag.auburn.edu/agec/pubs/budgets/
Arkansas	http://www.uaex.edu/depts/ag_economics/crop_budgets.htm
Florida	http://nfrec.ifas.ufl.edu/programs/enterprise_budgets.shtml
Georgia	http://www.ces.uga.edu/Agriculture/agecon/printedbudgets.htm
Iowa	http://www.extension.iastate.edu/agdm/crops/pdf/a1-20.pdf
Illinois	http://www.farmdoc.illinois.edu/manage/newsletters/fefo08_13/fefo08_13.html
Indiana	http://www.agecon.purdue.edu/extension/pubs/crop_guide_05.pdf
Kansas	http://www.ksre.ksu.edu/library/DesktopDefault.aspx?tabid=16#FarmRanch
Kentucky	http://www.uky.edu/Ag/AgEcon/pubsperson.php?searchterm=halig&db=faculty &ppage=halich.php
Louisiana	http://www.lsuagcenter.com/en/money_business/farm_business/budgets/
Minnesota	http://www.apec.umn.edu/faculty/wlazarus/tools.html
Missouri	http://www.agecon.msstate.edu/what/farm/generator/
North Carolina	http://www.ag-econ.ncsu.edu/faculty/bullen/bullen.htm
North Dakota	http://www.ag.ndsu.edu/pubs/ecguides.html
New Jersey	http://aesop.rutgers.edu/~farmmgmt/ne-budgets/conventional_practices.html
Ohio	http://aede.osu.edu/Programs/FarmManagement/Budgets/crops-2009/
Oklahoma	http://agecon.okstate.edu/budgets/sample_pdf_files.asp
Pennsylvania	http://agguide.agronomy.psu.edu/cm/sec12/sec12toc.cfm
South Carolina	http://cherokee.agecon.clemson.edu/crop_bud.htm
South Dakota	http://econ.sdstate.edu/Extension/otherlinks.htm
Tennessee	http://economics.ag.utk.edu/budgets.html
Texas	http://agecoext.tamu.edu/resources/crop-livestock-budgets/by-commodity.html
Virginia	http://www.ext.vt.edu/pubs/agecon/446-047/446-047.html

Appendix F Calculation of Break-even Risk Aversion Coefficient

McCarl, et al., (1987) developed a procedure to use Break-even Risk Aversion Coefficient (BRAC) to estimate CRRA. The concept behind BRAC metric (ρ) is that farmers prefer to grow field crop j_1 rather than j_2 when the utility from j_1 (R_1) is higher and vice versa. At a particular level of returns, the farmers will be indifferent between growing either crop j_1 or j_2. Hardaker et al (2004a) argued that the level of returns can be estimated as the certainty equivalent value which I the basis of SERF procedure. Hardaker, et al., (2004a) estimate ρ as the constant that drives the difference $B_3 = (CE_{j1} - CE_{j2})$ to zero, where j_1 and j_2 refer to two major field crops, $CE_{j1} = (1- \rho)* [V^{\#}(R_{j1})]^{1/(1- \rho)}$ and $CE_{j2} = (1- \rho)* [V^{\#}(R_{j1})]^{1/(1- \rho)}$; R_{j1} and R_{j2} are the returns from the two major crops; $V^{\#}(R_j)$ represents the average utility achieved from either crop. I choose corn and soybeans as the two major crops since they are grown in most states in the study region. Hardaker, et al., (2004a - Appendix B) illustrate the procedure to calculate ρ for power utility functional form (V).[37] Repeating this procedure for every US state generates different risk aversion coefficients for farmers across various US states.

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[37] See (Griffith, et al., 2009) for an alternative procedure to compute the risk aversion coefficient for negative exponential utility function (using Risk Root software).

Appendix G Break-even prices for miscanthus replacing wheat

Table 3.G1: Break-even price for miscanthus when planted in wheat fields ($/ton)*

	Crude Oil Price Scenario		
State	**I. Low**	**II. Reference**	**III.High**
FL	51.66	53.75	57.92
GA	49.66	51.68	55.70
IL	63.70	66.10	70.86
KY	41.36	43.74	48.51
MN	31.21	32.82	36.04
MS	47.78	49.86	54.02
NC	50.83	52.72	56.48
ND	42.37	44.01	47.26
NE	49.50	51.16	54.45
OH	56.68	59.25	64.35
OK	44.38	45.71	48.36
PA	55.69	57.98	62.54
SC	38.95	40.72	44.25
SD	46.23	47.75	50.78
TN	47.38	49.44	53.56
TX	37.60	38.80	41.20
WI	46.78	49.04	53.55

* These dollar values refer to the average break-even price required for miscanthus to replace continuous wheat crop in selected states.

These break-even prices for planting wheat fields are similar to the break-even price values presented in table 3.10 (various crops) and figure 3.8 (corresponding to corn-soybean rotation). These results confirm that energy crops have to be supported in selective US states because the break-even prices (and profitability) vary by state and by the crude oil price scenario.

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CHOICE OF OPTIMUM FEEDSTOCK PORTFOLIO FOR A CELLULOSIC ETHANOL PLANT – A MULTI-PERIOD LINEAR PROGRAMMING SOLUTION

4.1 Introduction

Future cellulosic biorefineries are expected to be large-scale facilities using multiple sources of feedstocks. Determining the optimal combination of feedstocks for these biorefineries involves a number of considerations: (i) assuring a reliable supply and uniform quality of biomass over the entire productive lifetime of cellulosic biorefinery; (ii) lowering procurement costs (harvest, baling, transport, storage, and seasonal costs); and (iii) reducing in greenhouse gas (GHG) emissions to qualify as a cellulosic biofuel under the federal renewable fuels standard or similar regulations, and possibly for tradable GHG credits . To ensure that cellulosic biomass feedstock meets these requirements, biorefineries take a lead role in developing their feedstock supply. Since the biorefineries control the extent of acreage contracted with one or more feedstocks, their feedstock procurement process would resemble a vertically integrated operation where the suppliers deliver cellulosic feedstock as per the needs of the biorefinery which essentially gets control of fields planted and feedstocks supplied to the biorefinery. In this paper, I evaluate the spatial and temporal patterns of such vertically integrated biomass procurement that include both perennial and annual agricultural feedstocks.

Biorefineries constructed in the Midwest are likely to draw from two major types of agricultural feedstocks: (1) energy crop biomass derived from perennial grasses such as switchgrass, miscanthus, and mixed grasses and (2) agricultural residue biomass derived from annual field crops such as corn, wheat, and barley. While agricultural residues are already produced along with feedgrains, perennial grasses are not yet grown commercially

Table 4.1: Differences between agricultural residues and energy crops

Feedstock Type	Annuals	Perennials
Crops	Corn stover, Wheat or Sorghum straw	Miscanthus, Switchgrass
Available biomass for harvest (dry tons/ac)	1 – 1.25[1] (harvest limited quantities every year or larger quantities once every 2 - 3 years)	10 maximum[2] (30% year 1; 70% year 2; 100% years 3 – 7; 80% years 8 – 10)
Standard deviation of yield in percent terms	Relatively stable – depends on how much is collected	25%[3]
Typical harvest span[#]	July – December	November– February
Contracting	Farmers allow periodic harvesting[4]	Need to be harvested every year or season[5]
Cost of biomass raw materials	\$20 - \$25 per ton	\$30-\$45 per ton
Harvest costs	Low	High
Transport costs	High, due to low biomass density and large collection area	Slightly lower, due to high biomass density
Theoretical ethanol conversion rate (gallons/dry ton)	99 – corn stover 96.4 – wheat straw[6]	106.1[7]
Conversion rate at 70% of theoretical maximum	69.3	74.3
GHG emissions[8] **(based on actual conversion rate)**	Byproduct residues are not allocated any GHG emissions associated with corn grain production, only conversion related GHGs are considered	48,500 g of GHG per ton of cellulosic biomass (511-653 tons of GHG per million gallon of cellulosic ethanol)

[1] Assuming a collection rate of 33% of total straw produced as a coproduct with grains (footnotes continued in the next page)

[2] Maximum potential yield based on miscanthus yield
[3] Annual crop harvest starts with spring wheat harvesting in May/June and extends till corn harvesting in Oct/Nov/Dec ; energy crops are expected to be harvested by the end of the growing season and possibly into winter months
[4] Contracts can be written with an option (not) to harvest depending on the needs of the biorefinery
[5] If energy crops are grown in a field, harvesting biomass would be the only source of income from that piece of land – hence, the farmers growing energy crops would require harvesting every year
[6] Corn stover chemical composition: Arabinan (2.54% mass), Xylan (18.32%), Mannan (0.4%), Galactan (0.95%) and Glucan (34.61%) – corresponding to 44 Corn stover *Zea mays* Stalks and Leaves without cobs ; wheat straw composition: Arabinan (2.35% mass), Xylan (19.22%), Mannan (0.31%), Galactan (0.75%) and Glucan (32.64%) %) – corresponding to 154 Wheat Straw *Triticum aestivum* Thunderbird whole plant
[7] Switchgrass chemical composition: Arabinan (3.19%), Xylan (23.27%), Mannan (0.22%), Galactan (1.05%) and Glucan (33.04%) – corresponding to 126 Cave-in-rock high yield variety ; ethanol yield from switchgrass and miscanthus are will be comparable because both are herbaceous energy crops with similar physiological traits and chemical composition.
[8] Based on the default parametric assumptions based on GREET model version 1.8

on a large scale. Thus, biorefineries need to choose the total acreage and locations contracted for agricultural residues and perennial grass production/harvest. To address this question, I develop a cost minimization model that identifies the optimal temporal and geographical combination of perennial and annual feedstocks surrounding a biorefinery. The optimization problem accounts for the differences in characteristics between the two feedstocks (table 4.1). As a demonstration, I use this model to calculate the optimal feedstock mix for a representative biorefinery located in Hugoton, southwest Kansas.

The two feedstocks – perennial energy crops and agricultural residues – differ on various characteristics. Energy crops have higher biomass yields, which increase the density of biomass availability (more tons per unit area) and shrink the extent of biomass collection area. The climate hardiness of energy crops allows flexible harvest that extends into winter months. The disadvantages with the perennial crops are higher establishment costs, longer time delay to achieve higher yields, long term contracts necessary due to lack of alternative markets, and potential problems in clearing the lands planted with perennial crops. While the long-term contracts provide a secure revenue stream for farmers, they are more constraining for biorefineries.[1]

In contrast, agricultural residues have a different set of feedstock characteristics. The revenues from agricultural residues are secondary to revenues from feedgrains – hence, farmers are likely to be flexible with harvesting agricultural residues. Farmers also have the option of not harvesting agricultural residues depending on whether feedstock prices more than compensate for the added production costs and the value of leaving crop residues in the field to maintain soil quality. More importantly, biorefineries may prefer agricultural residues as feedstock because they result in greater reduction of greenhouse gas (GHG) emissions. The reduction in GHG emissions is typically greater with agricultural residues because residues are allocated little or none of primary crop production related GHG emissions. A major disadvantage with agricultural residues is the lower yield of biomass per acre than that of energy crops which increases the collection area radius and transport costs. A cellulosic biorefinery also has to consider production costs, harvest costs, transport costs, short-term versus long-term contractual commitments, life-cycle GHG emissions, and other factors, such as losses in biomass storage and ethanol yield differences across the two feedstocks. These factors will affect biorefinery's spatial and temporal choice of feedstocks within the feedstock collection area termed as 'harvest shed.' Typically, a

[1] While the long-term contracts enable biorefineries to secure biomass supply, the prices at which they will be purchased is expected to change over time depending on their production costs.

cellulosic biomass harvest shed encompasses farm fields within a 50-mile to 100-mile radius around the biorefinery. A harvest shed would be optimal if it can help reduce costs based on where (spatial) and when (temporal) the feedstocks are grown.

I first develop a general mathematical programming model that can serve as a decision tool for any biorefinery and address such tradeoffs across multiple feedstocks. The objective is to minimize the cumulative discounted costs of biomass procurement over the biorefinery's productive life. I model the spatial distribution by subdividing the harvest shed into multiple concentric circular zones. I estimate the optimal acreage to contract within each zone and the optimal time to plant, harvest, and replant over the life of the biorefinery. Quarterly intervals are chosen to account for seasonal cost variations. The transport costs vary depending on the density of availability of the feedstocks. Hence, the transport costs are endogenously determined based on the amount of biomass per unit area – for instance, total tons per square mile. The seasonal costs are endogenously determined based on transport costs. The environmental costs are endogenously determined based on the acreages planted with various feedstocks. The harvest costs are exogenous but different across the feedstocks; the studies that modeled harvest costs endogenous found no appreciable difference between keeping harvest costs constant versus determining them endogenously in the model . The storage costs were kept exogenous because they are likely to be the same irrespective of the feedstock. Other exogenous parameters include biomass yield, ethanol conversion rates, production costs, harvesting costs, long-term contractual commitment needed to procure perennial feedstocks, life-cycle GHG emissions, and the rate of storage loss.

The novel features of this modeling approach compared with existing studies are summarized below. (i) Existing studies treat the available biomass quantities in the region as exogenously given and then try to minimize procurement costs. In comparison, the proposed model treats biomass acreage to be harvested as an endogenous decision variable subject to overall biomass availability constraints;[2] (ii) transport costs are endogenously determined as a function of harvesting decisions which has not been done in any existing studies; (iii) the temporal yield patterns of energy crops are modeled explicitly that also affect feedstock acreage decisions unlike many other studies which use steady state average yields; (iv) the current model incorporates the flexibility available with agricultural residue harvest and the restrictions due to long term contracts with energy crops; (v) the possible impacts of GHG emissions on feedstock sourcing decisions are also incorporated in the model. As a result, this model provides better insights into the realities of biomass procurement.

The model's constraints include the land available for sourcing either feedstock. For example, a certain proportion of geographic area is assumed to be potentially available for supplying biomass within each concentric circular zone around the biorefinery. This assumption is required because the land around the biorefinery includes non-agricultural lands and farmlands not capable of supplying feedstocks. I assume that agricultural residues will be procured only from these prime croplands within each concentric zone

[2] Mapemba et al (2008) model acreage harvested as an endogenous variable. However, their analyses and results are specific to Oklahoma. This model extends their analysis by modeling a generic harvest-shed with a number of concentric circles around the biorefinery for any location.

because the prime croplands are usually planted with field crops, such as corn and wheat.[3] In contrast, I assume that dedicated energy crops can be grown either on prime cropland or on marginal croplands (e.g., pasture, fallow lands, and Conservation Reserve Program (CRP)). The perennial energy crops will displace field crops and be grown in prime croplands if their economic returns are competitive with the existing land uses.

I demonstrate the usefulness of the model using the case study of *Abengoa Bioenergy's* pilot plant in Hugoton, south-west Kansas. I illustrate the feedstock composition for a proposed cellulosic ethanol biorefinery of 53 million gallons or 200 million liters of annual capacity.[4] To simplify the analysis, only two feedstocks are considered: corn stover (an annual crop residue) and miscanthus (a perennial dedicated energy crop). Corn stover is produced every year along with corn grains; for miscanthus, I assume that cellulosic biomass will be supplied for 10 years before replanting is required. The biorefinery is assumed to operate for 20 years (80 quarters).

The potential harvest shed around the biorefinery is divided into six concentric circular zones with outer radii of 5, 10, 15, 20, 30, and 50 miles. Surrounding Hugoton, KS, prime croplands account for 12% of the geographic area, while marginal crop lands account for 10% of geographic area.[5] I evaluate two scenarios where the two feedstocks

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[3] This assumption will not be binding because, as the results show, the agricultural residues are only second choice feedstocks. The chances of growing row crops on marginal lands are rather slim because those lands are not profitably operable with row crops currently. I maintain the same assumption that row crops will not be economical in marginal lands over the next 10 years as well.

[4] *Abengoa Bioenergy's* initial production capacity will be 18 MGY which will later be expanded to 25-75 million gallons

[5] The remaining 78% of geographic area consists of agricultural lands where biomass is not harvested from and non-agricultural lands. For the case study, I assume that residues

are harvested in the same (simultaneous) season and in different or subsequent (staggered) seasons. These two scenarios help analyze the potential effect of harvest timing on the optimal feedstock composition (Table 4.2). In scenario A, both feedstocks are harvested in the third quarter of every year (July-Sept). In scenario B, agricultural residues and energy crops are harvested in subsequent third quarter (July-September) and fourth quarter (October-December), respectively.

Table 4.2: Alternative scenarios based on harvesting season and harvest shed demarcation

Scenario	A	B
Agricultural residues from prime croplands; Energy crops from prime and marginal croplands	Both feedstocks harvested during the same season (third quarter) of every year	Agricultural residues harvested in the third quarter; Energy crops harvested in the fourth quarter

The results from the optimization suggest that the cellulosic biomass raw material costs range from 60 to 70 cents per annual gallon of cellulosic biofuel. This estimate is in the ballpark of estimates from other biomass feedstock studies . Biorefineries would prefer to source a larger proportion of biomass from dedicated energy crops such as miscanthus in spite of their higher establishment and production costs. The proportion of energy crops was about 70% and 80% of cellulosic biomass raw materials in scenarios A and B, respectively. The higher proportion of energy crops was due to the benefits of higher yields and dense availability of biomass (tons per acre or tons per square mile around the biorefinery). The increase in energy crops proportion in scenario B, compared to scenario A, suggests that the ability to spread biomass harvest during lean seasons would be a preferred characteristic. In both scenarios the spatial distribution turned out to be similar:

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can be contracted only from prime croplands, while energy crops can be grown from either on prime or on marginal croplands.

the energy crops were grown closer to the biorefinery, while the agricultural residues were transported from fields farther from the biorefinery. For energy crops, the higher density of biomass availability (in scenarios A and B) and staggered harvesting (in scenario B) offset higher production costs. The staggered harvesting reduced biomass raw material costs because it increased the proportion of energy crops in fields closer to the biorefinery which in turn reduced transport costs.

The proportion of energy crops and agricultural residues depended on two factors: the extent of marginal croplands available to grow energy crops, and the costs of sourcing either feedstock from their 'outer margins.' To illustrate, let the energy crops be grown within 15 miles radius and agricultural residues be grown within a 30 miles radius around the biorefinery. Energy crops would be part of the optimal feedstock mix as long as the material, transport and other costs of transporting it from a 15 mile radius were lower than the total cost of acquiring agricultural residues from a 30 mile radius. Hence, the delivered costs of the two feedstocks, which in turn depend on the acreages planted, would be used to determine the optimal combination of feedstocks. These results for an individual biorefinery reflect the outcome from other studies that estimate optimal feedstock composition of annual and perennial feedstocks at national level . The environmental costs did not seem to affect the optimal biomass portfolio much. Even when environmental costs rose, the proportion of energy crops declined only slightly from 73% to 69%.[6]

The optimization results generated shadow prices for binding land acreage constraints. These shadow prices represent the value that biorefineries place on an additional acre (or ton) of energy crops or agricultural residues grown within the harvest

[6] by increasing the prices of GHG emissions from $15 to $50 per ton of carbon dioxide

shed. These shadow prices can be interpreted as the maximum amount that the biorefineries are willing to pay to have one additional acre of a particular feedstock. The biorefineries can pay a few more dollars not exceeding the shadow price amount. If the additional payment brings in another acre or retains the last acre, then the biorefinery would still reduce its biomass raw material cost. The shadow prices ranged from $2-8 per ton for energy crops grown in fields located within a 10 mile radius. The shadow prices ranged from $5-16 per ton for agricultural residues grown within a 10-20 mile radius. The salient feature of the shadow prices was that the shadow prices varied significantly over time. The shadow prices for agricultural residues were higher whenever energy crop output is lower. For example, the additional value (shadow price or premium) placed on agricultural residues was $16 per ton during the first year of operations but it declined gradually over 20 years.[7] The shadow prices for energy crops were low in the beginning years; it gradually increased over time. The yield patterns of both feedstocks and land restrictions determined these results. The shadow prices for the zones with binding land acreage constraints showed similar temporal pattern. The shadow prices gradually declined with an increase in the distance of the fields/zones from the processing plant. Hence, the biorefineries could adopt a differential pricing strategy depending on the location or distance of the fields from the biorefinery. The lower material costs could justify a larger price premium (shadow price) paid for agricultural residues. Adding the shadow prices to the corresponding material and delivery costs would make both feedstocks comparable at

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[7] For instance, in case of scenario B, the price premiums for increasing agricultural residue by an acre fell to $6 per ton in years 2, and gradually declined with increased supply of biomass from energy crops.

the margin in every zone and every year, in other words these would also represent free market feedstock prices.

The shadow prices for annual feedstocks declined as the supply of energy crop biomass production ramped up over time. This shows that annual feedstocks are sought after only as buffer feedstocks to meet biomass demand when the energy crop output is low due to yield pattern differences. The shadow prices for energy crops were lower due to their yield patterns and contracting limitations. During the first two years of establishment phase, the energy crop yields would only be one-third and two-thirds of the maximum potential yield (10 tons per acre per year). So, the benefits from an additional acre of energy crop would accrue slowly over many years. Hence it would not be valued as much as an additional acre of agricultural residues. Moreover, the restriction that energy crop should be harvested during all 10 years created inflexibility and reduced the amount of shadow price for energy crops..

4.2 Literature Review

There is a growing body of literature on issues surrounding the supply of cellulosic biomass feedstock for biofuel production. These studies vary significantly in scope. Some studies focus on supplying a single biorefinery with a single feedstock, while other studies analyze the total potential supply of single feedstock within a region. Other studies analyze supply of multiple feedstocks to a single biorefinery or to a number of refineries within a region. These studies employ various methods, such as enterprise budgeting, supply curve analysis, simulation modeling, and mathematical optimization.

Single feedstock for a single biorefinery: These studies typically focus on low cost delivery of individual feedstocks based on mathematical programming models. Wang et al.

used a mixed integer linear programming model to study switchgrass harvest sheds. They evaluated how the harvest shed expands with an increase in biorefinery size (from 25 million gallons to 50 million gallons) and the impacts of weather on harvesting season, storage loss, and other related biomass supply issues such as type of baling operations (rectangular vs. round bales), transport and storage costs. Their results show that harvesting, baling and storage costs have to be included while modeling optimal feedstock combinations for biorefineries.[8]

Sokhansanj et al. (2006) developed a simulation-based optimization model called Integrated Biomass Supply and Logistics (IBSAL) model to study the supply of agricultural residues for day-to-day biorefinery operations. Kumar and Sokhansanj modified IBSAL to study switchgrass supply in alternative forms such as circular vs. rectangular bales, loaves or ensiled loafs. The IBSAL model identifies the optimal sequence of activities to harvest, transport and deliver cellulosic biomass to the biorefinery at a low cost. The biomass raw material costs were estimated at 70 – 73 cents per gallon of cellulosic ethanol. This estimate was substantially higher than US Department of Energy estimates of 40 – 45 cents per gallon reported in techno-economic studies . Currently, the IBSAL model is being expanded to evaluate supply decisions of multiple cellulosic feedstocks .

Single feedstock in a region: Many studies estimate the costs of crop establishment, management, harvest and transport costs of energy crops. These cost estimates for a particular enterprise, known as enterprise budgets, are commonly used to estimate the

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[8] Wang et al argued that rectangular bales will preferably be used immediately after the harvest due to shorter shelf life while the round bales would be stored with plastic cover and used during lean seasons

supply costs of energy crops such as miscanthus and switchgrass . These studies used agricultural input data derived from trial plots. The results from these studies showed that the potential for energy crops varied across regions depending on energy crop yields and production costs. While this approach has been adopted for many states, their results are largely limited to the region or state where the test plot sites are located. Other studies used formulas to estimate the transport costs and logistics of supplying biomass in various forms, such as chopped, rectangular bales, and round bales (Atchison and Hettenhaus, 2003; Gallagher, et al, 2003). They estimated harvest and baling costs to range from $11 to $20 per ton depending on feedstock and regional conditions. A few other studies evaluated the regional potential within the region, such as the number of biorefineries that can be supported within a state based on feedstock composition and available biomass quantity .

Multiple feedstocks for a single biorefinery: Dunnett et al. and Jacobson et al. argued that biomass yield levels of alternative feedstocks should be considered while determining the optimal supply of multiple feedstocks to a biorefinery. Epplin et al., (2007), and Mapemba et al., (2007, 2008) developed a series of linear programming models which studied the optimal combinations of naturally grown grasses and agricultural residues. Their objective was to analyze the combination of multiple feedstocks for a single biorefinery as well as multiple biorefineries in the state of Oklahoma by choosing the number of acres planted with grasses and other feedstocks as well as the number of harvesting units/machines required supplying cellulosic biomass.

Their mixed integer mathematical programming model maximized the net present value of profits for a biorefinery that used the saccharification and fermentation process over a 20 year time frame. They evaluated two major types of feedstocks: perennial grasses naturally grown on Conservation Reserve Program (CRP) lands and agricultural residues collected from prime croplands. They found that agricultural residues had a cost advantage over cultivating perennial grasses. The energy crops did not feature prominently due to low cellulosic biomass yield levels when their yield levels were at 3 to 4 tons per acre. These yields are much lesser than the potential yields of 8 to 10 tons per acre when energy crops are grown using intensive cultivation practices. According to their model, agricultural residues were preferred more to energy crop biomass due to low raw material costs.

I analyze a different set of questions compared to Mapemba et al (2007, 2008) and Epplin et al (2007). My model focuses on the optimal proportion of energy crops when energy crops are cultivated intensively (Table 4.1), specifically, on the spatial and temporal distribution of energy crops and agricultural residues within concentric circles around the biorefinery. By changing the parameters, my model can be applied to multiple locations or even different bioenergy outputs (generation of electricity from biomass).

Multiple feedstocks in a region: McCarl et al., evaluated the supply of agricultural residues and forestry biomass for electricity generation purposes. Their mathematical programming model (FASOM) was designed to maximize the objective of U.S. national social welfare defined as the net present value of the integral of biomass demand curves minus the integral of supply curves for the U.S. The FASOM model included biomass supply and harvest in agricultural and forestry sectors, the amount of land used for biomass harvesting, and shifting of lands between agriculture and forestry. The results showed that large amounts of biomass could be sourced within the United States to displace coal. Although the FASOM model does not have direct implications for an individual biorefinery's operations, it presents a set of constraints useful to model available land and required biomass for energy production.

Khanna, et al., used a mathematical programming called Biofuel and Environmental Policy Analysis Model (BEPAM) to evaluate the optimal composition of multiple feedstocks at the U.S. national level. They estimated the supply potential of perennial and annual feedstocks (energy crops and agricultural residues respectively) based on economic returns from row crops, dairy operations and available farmland in 41 states to supply one billion ton of cellulosic biomass by 2030. The BEPAM model predicted that energy crops would be economically more suitable in marginal croplands. The state level potential for energy crops varied with the regional characteristics, biomass yields (tons per acre), and relative price of alternative feedstocks.

Research Gaps and Contributions: The literature review shows that many studies focus on regional or national level biomass supply potential. While these studies are useful for policy analysis, there is a gap in identifying the optimal feedstock combination for individual biorefineries operations. The optimization models employed by Epplin et al. (2007) and Mapemba et al. (2007, 2008) partially address this issue. The results from these studies cannot be generalized because they emphasize a particular processing technology (saccharification and fermentation process), type of output (liquid biofuel), and their analysis is largely confined to the state of Oklahoma. I develop a more general model which evaluates biomass feedstock supply potential for multiple outputs, with an emphasis on the spatial and temporal patterns of harvest sheds, optimal acreage decisions and additional price premiums, if any, payable for cellulosic biomass.

The existing literature largely treats the feedstocks costs constant or exogenous. While it is a simpler approach, the biomass feedstock costs depend on acreage planting decisions and density of biomass availability. The major cost components such as harvest, baling and transport costs can potentially vary with harvest shed pattern. In this model I compute transport costs, seasonal costs, and environmental costs endogenously based on the decision variables (acreage and yield density).[9]

Biorefineries could pay a higher price to achieve a desired spatial and temporal pattern of harvest shed. The existing studies do not provide a reliable method to compute such price premiums. Using this model, I derive such measures using the shadow prices of binding land acreage constraints. These shadow values give an upper bound for price premiums payable for a feedstock in a zone at a particular time.[10] This model evaluates how GHG emission requirements affect the optimal composition of biomass feedstocks.

4.3 Model

Consider a generic biorefinery with ethanol production capacity PC (million gallons/quarter). Its biomass raw material requirements can be met with multiple feedstocks that include annually produced crop residues ($s = 1, 2, \dots S$) and perennials ($g = 1, 2, \dots G$). Agricultural residue yield levels are low (about 1.5 tons per acre per year); they

[9] The models by Mapemba et al., and Epplin et al., endogenize only the harvesting costs by choosing the number of harvesting units. Their results show that the number of harvesting units was cut in half when harvesting costs are determined endogenously. But the harvesting costs remained at $11/ton irrespective of whether they are determined endogenously or whether they were treated exogenous. A possible reason for this result is the change in other assumptions: for instance, the harvesting units would have been assumed to work 24 (12) hours a day when the harvesting costs were endogenously determined (maintained exogenous).

[10] These shadow prices show the cost savings realized by adding or retaining one more acre for biomass feedstock supply.

are annually produced as coproducts with feedgrains. Perennial energy crop yields are relatively high; they are productive for τ_g years (normally 10 years). Since the establishment costs of perennial crops are high, it is not economical to remove a perennial crop soon after establishment. Hence, the farmers would seek assured contracts to sell all energy crop biomass produced for τ_g years . This farmer requirement alters how biorefineries design their harvest shed and enter into contracts for biomass. The commitment of harvesting perennial energy crops for τ_g years is imposed as a constraint in the model. This restricts that the land allocated to perennial energy crops would be retained under energy crops for τ_g years. All biomass produced in those fields are assumed to be purchased by the biorefinery.[11] The model is formulated over quarterly intervals (q) to study how seasonal cost differences affect biomass supply and storage. The quarterly intervals match the harvesting pattern of feedgrains and cellulosic biomass that usually extends over three months during a crop year.[12] The quarterly intervals also help include storage and seasonal costs that help maintain regular supply of biomass during the peak and lean seasons of biomass harvests.

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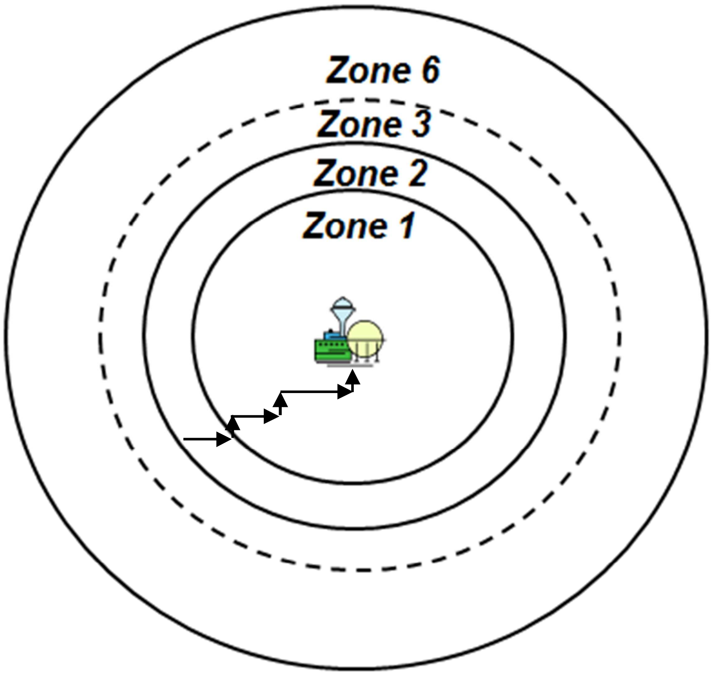
[11] The farmers do not have any other alternative markets within the harvest sheds and rely entirely on the single biorefinery which requires energy crops as raw materials.

[12] Monthly intervals were not chosen due to lack of sufficient information on monthly differences in perennial energy crop yields.

Figure 4.1: Concentric circular harvest shed area around the biorefinery (arrows represent perpendicular roads used for transport):



The harvest shed is assumed to be circular with the biorefinery located at the center (figure 4.1). The harvest shed is divided into concentric circular production zones ($z = 1,2,\ldots Z$), each zone corresponding to a concentric circular zone of outer radius of R_z and inner radius of R_{Z-1} miles. Each zone consists of both agricultural and non-agricultural lands. I eliminate the non-agricultural and land unsuitable for producing cellulosic biomass by estimating the available fraction of the area for energy crop production or agricultural residue collection. The available area is modeled as a fraction of total geographic area in each zone and is denoted by the symbol σ (σ_{sz} for annual feedstocks (s) and σ_{gz} for perennial feedstocks (g)). The harvested acreage is assumed to be distributed uniformly within every zone of the harvest shed.

Total transport costs (CT) and transport distance depends on the density of biomass availability i.e. CT is a function of (acreage planted * yield / zone area). Thus the transport costs are determined endogenously in the model. Transport costs include loading, unloading, and trucking costs. French gave an expression for transport cost calculations for circular harvest sheds. For a circular harvest shed, the total costs for transporting biomass can be written as $TC = N\, a_0 + \int_0^{2\pi} \int_0^{R} w\ a_1\, D\, r^2\ dr\ d\theta$ where TC is the total transport cost during a quarter (in dollars), N is the total amount of biomass required by the biorefinery (in tons), a_0 is fixed costs of transport equipment that do not depend on distance, loading and unloading (in \$/ton), a_1 is variable costs (\$/ton-mile), w is a constant parameter to convert air distance to road distance, D is the density of biomass within the circular harvest shed, and R is the outer radius of the circular harvest shed (French, 1960).[13] For a concentric circular harvest shed, I modify the above equation. The total amount of biomass from zone *z* is set to N_{zq}; range of radii is set to R_z and R_{z-1}; and biomass density within zone *z* is set to D_z to reflect the concentric circular zone variables.

$$TC \quad = N_{zq}\, a_0 + \int_0^{2\pi} \int_{Rz-1}^{Rz} w\ a_1\, D_z\, r^2\ dr\ d\theta \qquad (1)$$

In equation (1), D_z is the density of biomass availability in tons per square mile in zone *z*. It is substituted with another equivalent expression $D_z = N_{zq} / \pi R_z^2$. Similarly, the total amount of all cellulosic biomass from zone *z* can be expressed as $N_{zq} = [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}]$. Substituting both expressions for N_{zq} and D_z, the cost of transporting biomass from zone z is calculated as following:

$$TC_z = N_{zq}\ [a_0 + a_1\, {}^2\!/_3\, w\, \pi\, (R_z^3 - R_{z-1}^3)/(R_z^2 - R_{z-1}^2)] \qquad (2a)$$

[13] This is obtained by combining equations (2) and (5) in French (1960)

$$TC_{zq} = [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}] *$$

$$[a_0 + a_1\ {}^2/_3\ w\ \pi\ (R_z^3 - R_{z-1}^3)/\ (R_z^2 - R_{z-1}^2)] \qquad (2b)$$

Summing the transport costs across all zones, the total transport costs CT_q in quarter *q*

$$CT_q = \sum_z [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}] *$$

$$[a_0 + a_1\ {}^2/_3\ w\ (R_z^3 - R_{z-1}^3)/(\ R_z^2 - R_{z-1}^2)] \qquad (3)$$

Equation (3) is added to other costs that are minimized in the objective function. Note that CT_q is dependent on the acreage decision variables A_{szq} and A_{gztq}. Assuming transportation is done through perpendicular roads, the value of *w* can be approximated at √2.[14]

Current developments in pilot cellulosic plants indicate that biomass will largely be stored on field and transported to the biorefinery as and when needed for processing. Moreover, moving the entire harvest of biomass during the harvest season is difficult due to logistical issues and storage capacity limits . Transporting biomass during different seasons leads to seasonal costs. The seasonal cost fluctuations arise due to changes in diesel fuel and labor costs. The differences in labor costs are not considered for the following reason. Harvesting cellulosic biomass requires skilled labor that operates expensive harvesting equipment (tractors, collectors). The cost of skilled labor is relatively steady during peak

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[14] With perpendicular roads, $a^2 + b^2 = c^2$, where a = distance traveled north-south, b = distance traveled east-west, and c = air distance. Upon normalizing both a and b, $c^2 = 2$ or c = √2. That is, the sum (a+b) is also equivalent to multiplying c with √2. For example, consider the air distance of a field from the biorefinery is 10 miles. With perpendicular roads, the actual distance traveled would be 6 + 8 = 14 miles, derived from the relationship $6^2 + 8^2 = 10^2$. Multiplying 10 with √2, gives 14.14, a close approximation to the actual travel distance of 14 miles.

and lean season; hence, there will not be much difference in costs across different seasons.[15]

The fuel costs do change over seasons affecting biomass procurement costs . The seasonal costs (CL) are computed by multiplying the transport costs and harvesting costs with a factor ω_q. This factor estimates the increase or decrease in costs over the four seasons. The base or reference season is taken to be the second quarter extending from April-June. The seasonal costs are endogenous because it depends on transport costs. Material costs (CM), harvest costs (CH), and storage costs (CS) are assumed to be exogenous and treated as constants in the model. All these costs are maintained the same across all zones, expressed in terms of dollars per ton. This assumption is reasonable because these cost components are relatively the same irrespective of the field location within the harvest shed. Other parameters include biomass yield patterns of annual and perennial feedstocks (Y_s, Y_g respectively), storage costs (d_s, d_g), proportion of biomass lost in storage (ε_s, ε_g), the amount of biomass to be maintained in the inventory for continuous functioning of the biorefinery (minimum inventory required, *MIR*), ethanol yield per ton of annual and perennial feedstocks (K_s, K_g), fixed and variable cost components of transport costs per ton mile (a_0, a_1), and the fraction of area available to plant either feedstock within each zone (σ_{sz}, σ_{gz}).

The use of cellulosic biomass for bioenergy production has environmental benefits such as reduced GHG emissions and environmental costs such as, increased soil erosion,

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[15] Unskilled labor wages is more likely to fluctuate over seasons

and greater use of chemicals (herbicides and insecticides). The promotion of biofuels to reduce GHG emissions has led to accounting of GHG emissions at different life cycle stages such as biomass feedstock production, biomass conversion to ethanol, and final distribution. Leading models such as Argonne National Laboratory's GREET model use this approach to compare the environmental implications of using alternative feedstocks for bioenergy production . I use GREET model's GHG emissions data to compute the environmental costs (or benefits) of using alternative feedstocks.

Table 4.3: Lifecycle GHG Emissions from energy crops and agricultural residues[1]

Category	**Fermentation process**	
GHG emissions	**Energy crops (herbaceous biomass)**	**Agricultural residues (corn stover)**
In grams per million BTU of cellulosic ethanol[2]	4589	-6999
In tons of CO_2e per million gallon [3]	350	-534
Net change in emissions due to energy crops compared to agricultural residues (CO_2e tons per million gallon)	884	0 [4]

Source: GREET model v1.8c

[1] Emissions embodied in using farming equipment, fertilizers, pesticides and transportation of biomass are included

[2] These numbers are taken from GREET model (see the underlying excel sheet, EtOH worksheet, summary table 4). These data are sum of two forms of emissions – CO_2 and other forms of GHG emissions from biofuels. A positive (negative) number indicates an overall increase (decrease) in GHG emissions

[3] Ethanol energy content = 76,300 BTU/gallon; grams per gallon is converted into tons per million gallon by multiplying and dividing by 1,000,000

[4] Emissions from agricultural residues are normalized at zero

Table 4.3 data correspond to GHG emissions from the entire life-cycle (biomass cultivation, harvest, transport, processing, and distribution of fuels) in producing and processing biomass for cellulosic ethanol. The positive (negative) numbers refer to an increase (decrease) in GHG emissions due to that processing pathway.[16] Since the objective of my study is to compare two alternative feedstocks, I consider the emissions from agricultural residues as the baseline. That is, the environmental cost (CE_s) of using agricultural residues is normalized to zero.

As seen from table 4.3, the environmental costs vary with the processing technology. Energy crops emit more GHG than agricultural residues (+884 tons per million gallons) under fermentation processing technology. I compute the environmental costs by multiplying the GHG credits in table 4.3 by an expected GHG price. A reduction of GHG emissions by one metric ton results in one GHG credit. The environmental costs depend on the amount of annual versus perennial feedstocks processed which in turn depends on the acreage decision variables. Hence, the environmental costs are also endogenously determined together with transport and seasonal costs. I exclude the 'indirect' GHG emissions associated with land use changes due to lack of scientific consensus on how to estimate them .

The biorefinery's decision problem is to minimize the net present value of cumulative biomass procurement costs over the time period of its entire operations (e.g. 15-20 years). The total biomass procurement costs include payments made directly to farmers for biomass material (CM); payments made to contractors for harvesting (CH), transport costs (CT), seasonal costs (CL); payments made to maintaining on-site storage structures (CS), and internalized environmental costs (CE). The decision variables are (i) the acreage

[16] Even though the emissions data are positive for certain biomass feedstocks or processes, biofuels help reduce GHG emissions compared to GHG emissions from fossil fuels.

A_{szq} contracted to harvest agricultural residue *s* in quarter *q* in zone *z*, and the acreage A_{gztq} contracted to plant energy crop *g* in year *t* in zone *z* and, (ii) the amount of feedstock (*s*, *g*) processed during every quarter *q*. The storage quantities are implicitly determined by subtracting the amount of biomass processed from the amount produced during each quarter. Note that, if some acreage is planted with energy crops in year *t*, then that acreage will be retained with energy crops for the next τ_g years. This restriction does not apply to agricultural residues.

Model Equations

The symbolic notations of the model are explained below:

Subscript notation:

s = Annual agricultural residue feedstocks such as straw or stover [s = 1, 2, … S]

g = Perennial grass feedstocks such as miscanthus, switchgrass [g = 1, 2, … G]

z = Concentric circular production zone [z = 1, 2, … Z]

q = The production/harvesting time period (quarter) [q = 1, 2... Q]

t = Year in which perennial crops are planted [t = 1, 2, … T]. Perennial crop *g* is assumed to supply biomass for τ_g years following establishment; hence, the perennial crop *g* established in year 3 (t=3) will supply biomass starting in year 3 until 3 + τ_g

Parameters:

CM_s, CM_g = Unit material cost of feedstocks s and g (dollars per ton, price paid to farmers)

CH_s, CH_g = Unit harvest cost of feedstocks s and g (dollars per ton)

CT_z = Unit transport cost of feedstock from zone z to the biorefinery located at the center (dollars per ton)

CS_{sq}, CS_{gq} = Unit storage cost of feedstocks s and g in quarter q (dollars per ton per quarter)

CE_{gq} = Unit incremental environmental cost of perennial feedstock g in quarter q (dollars per ton)

CX_{szq} = Total exogenous costs of annual feedstocks s processed in quarter ($CM_s + CS_s + (1+\omega_q)\ CH_s$, dollars per ton)

CX_{gzq} = Total exogenous costs of perennial feedstocks g processed in quarter ($CM_g + CS_g + (1+\omega_q)\ CH_g + CE_g$, dollars per ton)

Y_{gtq} = Yield of perennial feedstock g, planted in year t, for quarter q [Fixed pattern of yields in tons per acre per quarter; e.g. in scenario B, miscanthus crop planted in year t = 3 will yield 3.33 tons/acre in quarter 12, 6.67 tons/acre in quarter 16, 10 tons/acre every fourth quarter during quarters 20 – 36, 8 tons/acre every fourth quarter during quarters 40 – 48, and 0 tons in all other quarters If miscanthus crop were planted in year t = 5, then the same yield pattern will be shifted from quarters 20 through 56. The amount of biomass available in quarter q depends on the planting year (t) of miscanthus]

Y_{sq} = Yield of annual agricultural residues *s* that remains constant – harvested only once in a year either during the third or during the fourth quarter)

Ψ_{sq}, Ψ_{gq}= Quantity of feedstock (s, g) produced within the entire harvest shed during quarter q (tons)

D_{sq}, D_{gq} = Quantity of feedstock s and g processed at the biorefinery during quarter q (tons)

ω_q = Factor to compute seasonal costs related to transporting; second quarter is taken as the reference season, i.e. $\omega_{q=2}$ is normalized at 1 (see table 4.5)

δ = Quarterly discount factor

d = Storage cost parameter (dollars per ton per quarter)

ε_s = Rate of loss of agricultural residue due to storage (percentage per quarter)

ε_g = Rate of loss of perennial grasses due to storage (percentage per quarter)

PC_q = Quarterly ethanol processing capacity (gallons)

K_s, K_g = Ethanol output for feedstock s and g respectively (gallons per ton)

MIR = Minimum Inventory Requirement (tons)

Q = Terminal time period

P_{GHG} = Price for one ton of greenhouse gas ($ per ton of CO_2equivalent)

GC_g = Greenhouse gas credit for using energy crops, in comparison to using agricultural residues (tons of GHG per million gallon of cellulosic ethanol)

a_0 = Fixed component of transport costs ($ per ton of feedstock)

a_1 = Variable component of transport costs ($ per ton-mile)

σ_{sz} = Fraction of total land area available in zone z to harvest annual feedstock s (in percentage)

σ_{gz} = Fraction of land area available in zone z to harvest all perennial feedstocks g (in percentage)

ZA_z = Total geographic area within zone z (acres)

R_z = Outer radius of zone z (miles)

w = factor to convert radial distance to road distance; with perpendicular road network, w equals $\sqrt{2}$

Objective function:

Minimize discounted cumulative feedstock procurement costs over Q quarters:

$$\sum_q \delta^q * [\sum_g \sum_z \sum_t CX_g * Y_{gtq} * A_{gztq}) + \sum_s \sum_z CX_s * Y_s * A_{szq}) \\ + (1+\omega_q)\, CT_q \\ + d * \sum_s X_{sq} + d* \sum_g X_{gq} + CE_{gq}]$$

where CX refers to exogenous costs of cellulosic biomass, CT refers to endogenously determined transport costs and d*X refers to storage costs

with respect to decision variables:

A_{szq} = Acreage contracted to harvest annual feedstock s in quarter q, zone z (in acres)

A_{gztq} = Acreage planted with perennial feedstock g in year t, zone z (in acres; yield pattern of perennial feedstocks is described in tables 4.1 and 4.5)

X_{sq}, X_{gq} = Storage levels (stock variable, either at the biorefinery or on farm fields) of feedstock s and g at the end of quarter q (in tons)

D_{sq}, D_{gq} = Quantity of feedstock (stover s, grasses g) processed/demanded in quarter q – which are implicitly determined as residuals upon choosing X_{sq}, and X_{gq}

subject to the following accounting relationships (E1-E4) and constraints (E5-E10):

Accounting relationships:

E1: Zone area ZA_Z (in acres) around the biorefinery extending from zonal radius R_{Z-1} to zonal radii R_Z (in miles); the constant 640 converts square miles of area to acres

$$ZA_Z = 640\,\pi\,(R_Z^{\,2} - R_{Z-1}^{\,2})$$

E2: Total biomass produced during every quarter (Ψ_q) is computed by multiplying the acreage harvested (A_{szq}, A_{gztq}) with yield (Y_{sq}, Y_{gtq})

$$\Psi_{sq} = \sum_z Y_{sq} * A_{szq}$$

$$\Psi_{gq} = \sum_z \sum_t Y_{gtq} * A_{gztq}$$

$$\Psi_q = \sum_s \Psi_{sq} + \sum_g \Psi_{gq}$$

E3: Transport costs (equation (3) from section 3):

$$CT_q = \sum_Z [a_0 + a_1\,{}^2/_3\,w\,(R_Z^{\,3}-R_{Z-1}^{\,3})/(R_Z^{\,2}-R_{Z-1}^{\,2})] * [\sum_s A_{szq} * Y_{szq} + \sum_g \sum_t A_{gztq} * Y_{gtq}]$$

E4: Environmental costs (CE_{gq}) of perennial feedstocks are computed based on expected GHG prices (P_{GHG}) and GHG credit (GC_g). In case of fermentation technology, this term will be positive (additional costs due to using energy crops).[17]

$$CE_{gq} = P_{GHG} * GC_g * D_{gq} * K_{gq}/1000000$$

Constraints:

E5: Land availability constraints for perennial feedstocks:
The acreage harvested with grasses (A_{gztq}) and agricultural residues (A_{szq}) should be less than the available area from crop lands (σ_{sz} ZA_z) and marginal (σ_{gz} ZA_z) croplands. This constraint has to be satisfied in every quarter q across all zones z.[18]

$$\sum_g \sum_t A_{gztq} \leq \sigma_{gz} ZA_z$$

Land availability constraints for annual feedstocks

$$\sum_s A_{szq} \leq \sigma_{sz} ZA_z \qquad \text{for all q and z}$$

E6: Biomass mass balance constraints: Biomass supplied from fields and storage should equal the sum of biomass processed and inventoried in each quarter:

Biomass produced in quarter q (Ψ_q) + Stocks from previous quarter (q-1) = Biomass used for biofuel conversion in quarter q ($D_{gq} + D_{sq}$) + Ending stock for quarter q

$$\Psi_q + [(1 - \varepsilon_s) * \sum_s X_{s\,q-1} + (1 - \varepsilon_g) * \sum_g X_{g\,q-1}]$$
$$= D_{gq} + D_{sq} + [\sum_s X_{sq} + \sum_g X_{gq}]$$

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[17] The division by 1000000 converts ethanol gallons to million gallons.

[18] A different formulation of land allocation is where both feedstocks can be harvested from all available lands. The restriction to source agricultural residues from prime croplands and energy crops from marginal croplands can be relaxed in the following manner. When all feedstocks can be grown in both prime and marginal croplands, the constraint E5 is replaced with the following. The total proportion of available (prime and marginal) cropland in every zone will be σ_z where $\sigma_z = \sigma_{sz} + \sigma_{gz}$. The summation over years (t) adds up the acreage allotted to energy crops that are planted at different times during the years 1 – 11. This constraint should be satisfied in every quarter q across all zones z.

$$\sum_s A_{szq} + \sum_g \sum_t A_{gzt} \leq \sigma_z ZA_z \qquad \text{for all q and all z}$$

E7: Biofuel produced has to meet or exceed the processing capacity (PC_q) in every quarter:

$$\sum_s K_s * D_{sq} + \sum_g K_g * D_{gq} \geq PC_q \qquad \text{for all q}$$

E8: Biomass stored at the biorefinery has to meet the minimum inventory required (MIR) at the biorefinery – only this quantity of biomass incurs storage costs. The excess biomass, if any, would be stored on field without storage costs.

$$\sum_s K_{sq} * X_{sq} + \sum_g K_{gq} * X_{gq} \geq MIR * PC_q \qquad \text{for all q}$$

E9: Terminal conditions for the last quarter (Q) are imposed by restricting the final period storage to zero after meeting the biomass processing requirements

Biomass supplied from the fields in final quarter Q + supply from the storage in quarter (Q-1) – Biomass used for conversion in Q = Ending stock for quarter Q = 0

$$\Psi_Q + \sum_s (1 - \varepsilon_s) X_{s\ Q-1} + \sum_g (1 - \varepsilon_g) X_{g\ Q-1} - D_{sQ} - D_{gQ} = \sum_g \sum_s (X_{sQ} + X_{gQ}) = 0$$

E10: Non negativity constraints of acreage and storage decision variables:

$$A_{szq} \geq 0;\ A_{gztq} \geq 0;\ X_{sq} \geq 0;\ X_{gq} \geq 0$$

The cost minimization problem is coded in GAMS and solved using MINOS solver. The chosen solver helps achieve globally optimal solutions when the objective function and constraints are convex sets ; in this model, they are linear yielding globally optimal solutions. The results from the optimization model include: (i) the minimized total cost of biomass, expressed in terms of dollars per annual gallon of ethanol, (ii) acreages of all feedstocks (annuals and perennials) harvested in each quarter in each zone, (iii) variations in biomass quantities processed versus maintained in storage, and (iv) shadow prices or price premiums to expand land acreage within each zone. Additional sensitivity analyses are conducted to analyze the impact of changes in exogenous parameters (e.g., land availability, change in material costs).

4.4 Case Study

For the case study, I consider a biorefinery with a capacity of 53 MGY. The geographic parameters are calculated for Hugoton, Kansas where *Abengoa Bioenergy* is building one of its pilot cellulosic ethanol plants.[19] There are similarities among various annual feedstocks in terms of harvesting flexibilities and stable biomass yield levels. Similarly, there are also similarities among various perennial grasses in terms of plantation establishment, productive life period (10 years) and yield patterns. Hence, I choose to represent annual feedstocks (s) with corn stover and perennial grass feedstocks (g) with miscanthus. Although only one annual and one perennial feedstock are used for this case study, the model results can be extended to other feedstocks.

The objective of the optimization problem is to minimize (cumulative) biomass feedstock procurement costs over 20 years (2011-2030), subject to following constraints: biomass availability by type and season, biomass requirements for processing and storage, land allocation restrictions for perennial energy crops, and the type of lands available to grow energy crops and corn stover (see generic model and table 4.2). At an average conversion rate of 70 gallons per ton, about 190,000 tons of biomass from both corn stover and miscanthus would be required during each quarter. To supply the required biomass, multiple harvests of corn stover and energy crops would be required.

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[19] *Abengoa Bioenergy* plans to use 75% of biomass from corn stover and 25% from energy crops, provided the latter becomes economically available

Harvest shed around Hugoton, Kansas

I focus on the harvesting decisions within a 50 mile radius harvest shed since previous estimates indicate availability of sufficient biomass potential within that area.[20] The circular harvest shed around the biorefinery is sub-divided into six concentric zones (z) with outer radii of 5, 10, 15, 20, 30 and 50 miles. The geographic area within a 50 mile radius around Hugoton, KS include the counties of Stevens, Morton, Seward, Stanton, Grant, Haskell in Kansas; the counties of Texas, Beaver and Harper in Oklahoma; the counties of Dallam, Hansford, Ochil-tree and Sherman in Texas; and the counties of Baca, Bent, Kiowa and Prowers in Colorado.

An average of 36% of the geographic area in these counties is classified as prime cropland. Crops such as corn, wheat, sorghum and barley that can supply agricultural residues make up two-thirds of cropland area in these counties. Hence, agricultural residues can potentially be collected from 24% of geographic area (two thirds of 36%). Since agricultural residue collection is rotated among fields, only a portion of these fields would be harvested in any given year. I assume that agricultural residues are harvested once every two years. Thus, 12% of geographic area (one half of 24%) would potentially be available to harvest agricultural residues during each year within 50 mile radius around Hugoton, KS. Although it is possible to supply agricultural residues from marginal lands, it is not likely to be significant because the additional returns from agricultural residues may not be sufficient enough to warrant growing row crops in marginal lands where the economic returns are low in general. For simplicity, I assume that feedstock acreage is distributed

[20] As the subsequent results show, this restriction is not binding – i.e. there is surplus unused land within the harvest shed of 50 mile radius

uniformly within each concentric circular zone. This assumption matches the assumption underlying equation (3) used for calculating transport costs .

Table 4.4: Land area available for harvesting cellulosic feedstocks – case study assumptions

		Harvest shed area is divided into two sections for the two feedstocks	
Zone – Outer Radius	**Geographic Area**	**Agricultural residues sourced from prime croplands @ 12% of geographic area** (σ_{SZ}=0.12)	**Energy crops sourced from prime and marginal croplands @ 22% of geographic area** (σ_{gZ}=0.22)
Miles	**Thousand Acres**		
Z_1 – 5	50	6	11
Z_2 – 10	201	18	33
Z_3– 15	453	30	55
Z_4 – 20	806	42	77
Z_5 – 30	1,813	121	221
Z_6 – 50	5,035	426	709

Energy crops can be grown in marginal croplands. The latter includes permanent pastures, rangelands, and Conservation Reserve Program (CRP) acres. Mapemba et al., (2008) estimated that 10% of geographic area can be classified as marginal cropland in the south-west Kansas and Oklahoma Panhandle areas (around Hugoton, KS). Energy crops can also be grown in prime croplands provided they are economically competitive; there is a possibility that farmers replant some of the prime cropland with energy crops.[21] The above calculations show that 12% of prime cropland could be available for energy crop production (where agricultural residues are not harvested from). Hence, a total of 22% of

[21] To grow energy crops in prime croplands, their economic returns have to be comparable with that of field crop returns. Since it is a farmer's decision to plant or not plant a field with energy crops, it is not explicitly modeled in my optimization model for the biorefinery. An extension of this research is to model a multi-objective optimization problem that models both biorefinery and farmers' decisions.

geographic area – 10% marginal lands and 12% prime croplands – is assumed to be available for planting energy crops. These assumptions are retained for all zones: σ_{sz} = 12% and σ_{gz} = 22% – see table 4.4. These assumptions are relaxed by conducting sensitivity analysis by changing the parametric values for σ_{sz} and σ_{gz}.

Decision variables

There are two sets of decision variables: (1) acreage planted with annual and perennial feedstocks, and (2) quantity of biomass processed versus retained in storage during each quarter.

(1a) For agricultural residues, there are potentially 480 acreage decision variables, i.e. 20 years * 4 quarters/year * 6 zones/quarter. However, agricultural residues are only harvested during the third quarter of every year (table 4.2). The yield is restricted to zero when biomass is not supplied from the fields during 1^{st}, 2^{nd} and 4^{th} quarters of each year.

(1b) For energy crops, the yield pattern is different; once established, energy crops can be harvested during the next 10 years (τ_g=10 years or 40 quarters). That is, energy crop established in year 1 will supply biomass during years 1-10, energy crop established in year 2 will supply biomass during years 2-11 and so on. If the energy crops are planted in each of the 20 years, then there are potentially 120 choice variables related to energy crop acreage (20 years * 6 zones/year). But as the biorefinery nears its shut down at the end of 20 years, the farmers may be unwilling to establish new acreages of perennial energy crops. To reflect this unwillingness, establishment of new perennial crops is restricted to years 1 through 11; this ensures that the crop planted in year 11 will be fully harvested by year 20. In this case, there are 66 choice variables associated with planting energy crops (11 years *

6 zones/year). The energy crop biomass may be harvested simultaneously with agricultural residues during the third quarter of every year (scenario A) or in a staggered manner during the fourth quarter of every year (scenario B).

(2) The second set of decision variables chooses the quantity of biomass processed versus the kept in storage, either at the biorefinery or on field. There are a total of 79 storage variables corresponding to all quarters except the last quarter (20 years * 4 quarters/year – 1). For the last time period (q = 80, denoted by Q) the storage level is restricted to zero to reflect the terminal condition.

Cost Parameters

The following section describes how the model parameters are estimated for the case study location in Hugoton, KS. The material or product costs refer to prices that farmers receive for agricultural residues and energy crops. For agricultural residues, the material costs cover opportunity costs such as potential revenues lost from selling residues as animal bedding material and the lost fertilizer value when residues are removed. I assume the material costs of agricultural residues at $22 per ton.[22] For energy crops, the material costs cover crop production costs and opportunity costs such as potential lost revenues (e.g., revenues lost from CRP payments or economic returns from earlier land uses). I assume the material costs of energy crops at $30 per ton.[23] I conduct sensitivity analyses to evaluate the impacts of changes in material costs on the optimal proportion of energy crop feedstock.

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[22] In 2009, farmers in south central Nebraska were paid an average of $22 per ton as material cost for agricultural residues supplied to Energy Grains Biomass LLC .

[23] Mooney, et al. and Wang, et al. estimated the material costs of energy crops at $25-35 per dry metric ton.

Harvest costs include fixed costs of machinery equipment and variable costs of chopping, raking, collecting, baling, hauling, and staging biomass within the farms. I estimate harvesting costs (HC) of agricultural residues and energy crops at $14 and $16 per ton, respectively, based on USDA reports . The harvesting costs for energy crops are slightly higher because of intensive use of machinery in handling energy crop biomass. These harvesting cost estimates are within the range of $11 to $20 per ton estimated by other studies (Epplin, et al., 2007; Sokhansanj, et al., 2006; Thorsell, et al., 2004; Wang, et al., 2009). Treating the harvest costs as an exogenous parameter is not limiting. The results from Epplin et al (2007) and Mapemba et al (2007, 2008) showed that harvest costs remained at about $11 per ton whether they were endogenized or held constant.

Transportation cost per ton mile is assumed at $0.28 per ton-mile based on previous estimates . The transportation costs are endogenously determined based on the acreages planted with either feedstock as shown in equation E3. For seasonal cost variations, I consider the (real) price fluctuations of diesel fuel at quarterly intervals – Jan-Mar, Apl-Jun, Jul-Sep, Oct-Dec. The first quarter serves as the reference point (normalized at 100%). The seasonal price differences (ω_q) during other quarters are given in table 4.5. The seasonal costs are computed by multiplying the average percentage changes for a particular season with harvest costs (CH) and transport costs (CT). The seasonal costs are also endogenously determined due to their dependence on transport costs.

Table 4.5: Seasonal cost variations based on quarterly diesel prices (1990-2009)

	Q_1 – Jan-Mar	Q_2 – Apr-Jun	Q_3 – Jul-Sep	Q_4 – Oct-Dec
1994-2010 Average	100%	105%	108%	109%

Source: EIA

Cellulosic biomass harvest is usually limited to a short harvest window, during the third or fourth quarter of every year. This requires construction of storage facilities, associated costs and biomass quantity losses in inventory . Mapemba et al. estimated that on-site storage would retain storage to supply cellulosic biomass for three weeks. In this case study modeled in quarterly terms, this is equal to storing 25 percent of quarterly biomass requirement (3 weeks out of a 12 week quarter). Any additional biomass would be stored on field eliminating storage costs or losses for the biorefinery. The storage will be maintained during all quarters except the final time period (Q = 80). The storage costs and the biomass lost in storage (both on-field and on-site) are estimated at $3/ton/quarter and 3% per quarter respectively .

The environmental costs of cellulosic biomass feedstocks are computed based on the amount of GHG emitted with processing agricultural residues or energy crops. Energy crops result in higher GHG emissions when processed using fermentation and saccharification technology (last row of table 4.3). The economic costs due to GHG emissions (CE_g) for energy crop feedstock are added to the objective function. I treat the emissions from agricultural residues as baseline. The GHG prices ranged from $0.10 – $5 per ton of GHG in the U.S. compared to $20-30 per ton in the European markets.[24] I use the expected GHG price level of $15 per ton of GHG; this is a reasonable estimate of GHG

[24] Over the past 2 years, GHG prices ranged from $0.25 to $5 per metric ton in Chicago Climate Exchange in the US and $10 - $25 in over-the-counter (OTC) exchanges in Europe. Note that revenues from GHG reduction will be realized in dollars only if the biorefineries become eligible to trade them. Firms such as Agra and AgRefresh working towards creating this new market for biofuels sector . Even if the biofuel projects become eligible for GHG trading, only a small part of the biofuels and biomass would satisfy the additionality requirement and become eligible for tradable GHG credits . Including environmental costs in the cost minimization problem ensures that the additional environmental value created for the society due to cellulosic biofuel use is accounted for.

price and frequently quoted by North American emissions management funds . To compute the environmental costs (or benefits), I multiply the GHG price of $15 per ton with the relative GHG emissions from energy crops.

4.5 Results

The raw material costs of cellulosic biomass for biofuel production are estimated for the parametric values reported in table 4.6. In scenario A, where both agricultural residues and energy crops are harvested simultaneously in the third quarter, the raw

Table 4.6: Parametric values for scenarios A and B in preliminary results

Parameter	Level in base case scenario
Costs of storage, d (per metric dry ton/year)	$12
Storage Loss (per year)	12%
Energy crops and stover grown in separate fields	
Land available for perennial energy crop cultivation	22%
Land available for stover collection	12%
Discount rate	2%
Minimum inventory maintained at the biorefinery facility (biomass worth 3 weeks of storage in a total of 12 weeks)	25%
Material costs ($/dry ton, modeled using Atchison and Hettenhaus, 2003)	
Energy crop	$ 30
Stover	$ 22
Harvesting costs ($/ dry ton)	
Grasses	$ 16
Stover	$ 14
Transport costs per ton mile	$0.28/ton mile
Seasonal costs	Reference season: quarter 1; seasonal cost factor (table 4.5) multiplied with transport and harvest costs
Environmental costs	$15/ton of GHG; quantities given in table 4.3

material costs are estimated at 64.5 cents per gallon.[25] In scenario B, where the agricultural residues are harvested in the third quarter and energy crops are harvested in the fourth quarter (staggered harvesting), the biomass raw material costs are estimated at 60.6 cents per annual gallon. The raw material costs are lower in scenario B because staggered harvesting helps reduce storage requirements and associated costs. These biomass raw material cost estimates are within the range of 60-75 cents per gallon reported in other studies.

Under the set of land and cost assumptions used in this study, the results suggest that energy crops can be expected to supply a significant portion of cellulosic biomass. The proportion of energy crops in the optimal supply stood at 70% and 73% of total biomass requirements in scenarios A and B respectively. In spite of higher material and harvesting costs, energy crops appeared in the optimal portfolio of raw materials due to two reasons. (1) Staggered harvesting reduce storage requirements in scenario B compared to scenario A (see table 4.2); hence, any feedstock that extends the harvest window and reduce storage requirements would be suitable as part of cellulosic biomass portfolio. (2) Reserving marginal croplands for exclusive cultivation of energy crops also contributed to a higher proportion of energy crop biomass.

The temporal distribution of the acreage planted/harvested for energy crops and agricultural residues is given in figure 4.2. The acreage under energy crops was less but remained steady over the 20 year period. In spite of less acreage, up to 70% of biomass was derived from energy crops. The long term land allocation restrictions and the higher yields

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[25] Cost per annual gallon
= (cumulative discounted cost of biomass over 20 years)/(total amount of biomass processed over 20 years)

of energy crops contributed to these results. In contrast, the acreage under agricultural residues fluctuated heavily. More acreage was allocated to agricultural residues whenever the energy crop biomass output was low. Hence, energy crops turned out to be the preferred feedstock. This result confirms the industry assertion that more cellulosic biomass would be derived from energy crops .

Figure 4.2: Acreage contracted (000 acres) with either feedstock – Scenario B

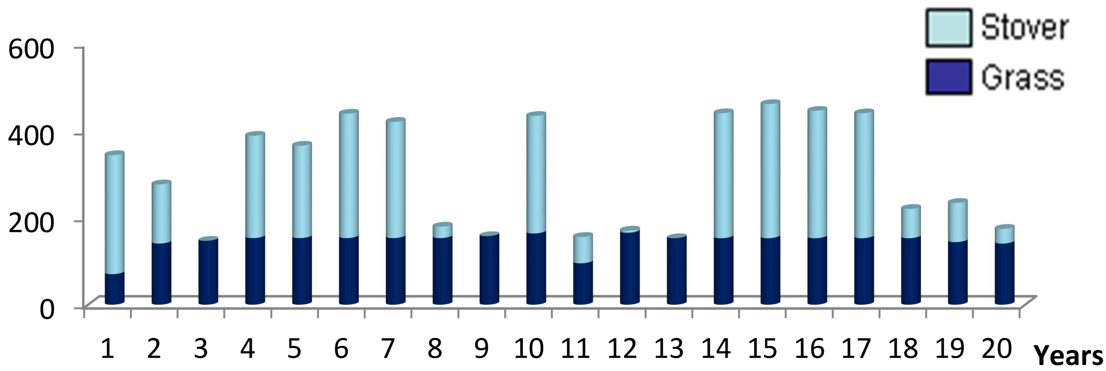
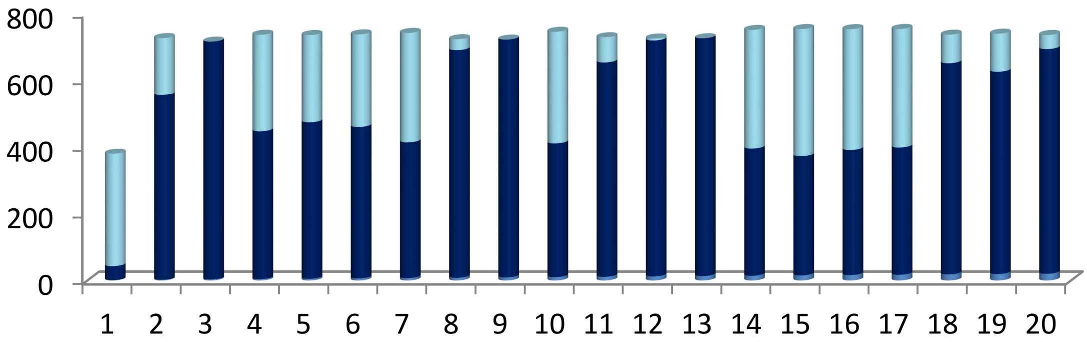


Figure 4.3: Composition of biomass used for biofuel production (000 tons) – Scenario B

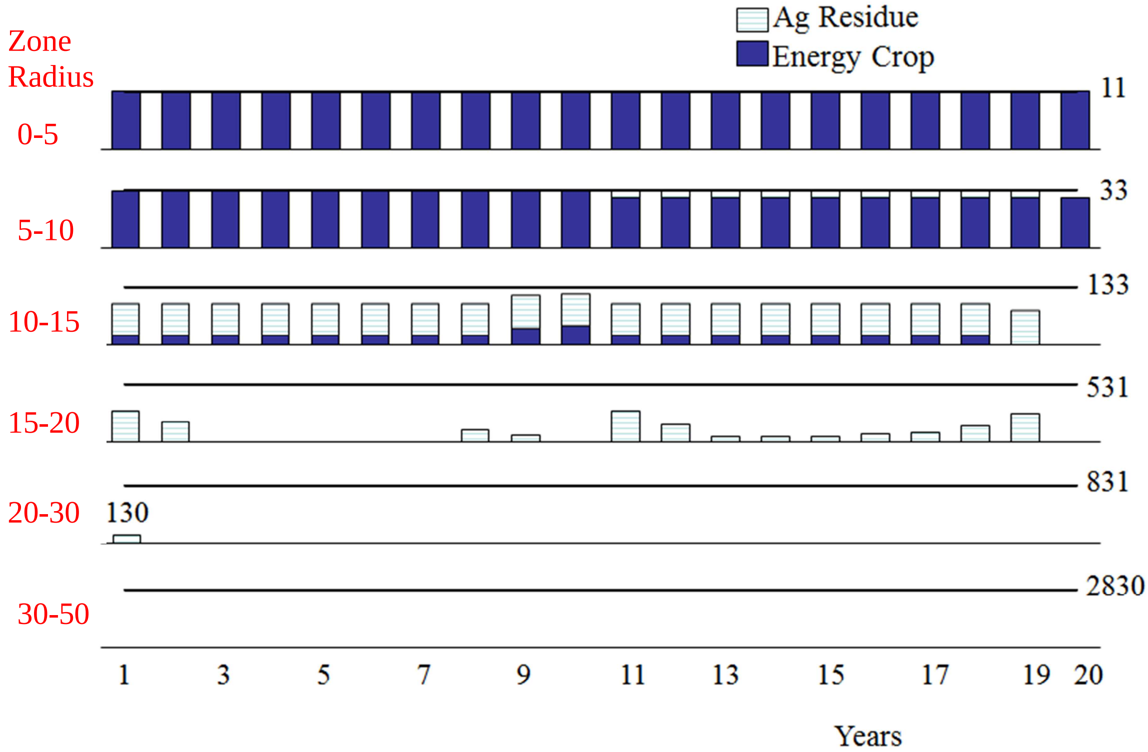


Even though a larger proportion of land (acres) corresponded to harvesting agricultural residues, the amount of agricultural residues (tons) was much less as shown in figure 4.3.

The spatial and temporal distribution of the harvest shed is given in figures 4.4 and 4.5 for scenarios A and B, respectively. The number on the right shows the sum of prime and marginal croplands in each zone (in thousands of acres). The results show that the harvest shed extends only up to 30 mile radius around the biorefinery (zone Z_5) in scenario A; the spread is even lower at 20 mile radius (Z_4) in scenario B. The geographic spread shrank in scenario B because the higher proportion of energy crops that produce more biomass per unit area. These results confirm the notion that whenever high yielding energy crops are included as part of feedstock portfolio, then the fields within a 20-30 mile radius would be sufficient to supply the biomass requirements for a biorefinery of about 50 million gallon capacity.

The optimal composition of feedstock depends on the economic trade-off between delivered costs, biomass density (tons per acre) and land available for harvesting alternative feedstocks. As an instance, consider how agricultural residues and energy crops are planted in various zones. Energy crops are grown in fields located closer to biorefinery. Agricultural residues are predominantly collected from fields/zones farther from the biorefinery. In the model, the fields closer to the biorefinery are ideally planted with energy crops and this forces collection of agricultural residues from fields that are farther away from the biorefinery. The lower material costs of agricultural residues enable a higher payment for transport costs from fields farther from the biorefinery as long as the combined material and transport costs of agricultural residues is lower than that of energy crops. Agricultural residues provide larger quantities of biomass whenever energy crop supply is low in years 1-2, and 10 when energy crops are established, and reestablished. The supply of agricultural residues is also higher during the middle years 4-7, and 14-17 due to lower costs of transporting agricultural residues from 10-20 mile radius rather than growing energy crops within a 10 mile radius around the biorefinery (and other associated land constraints).

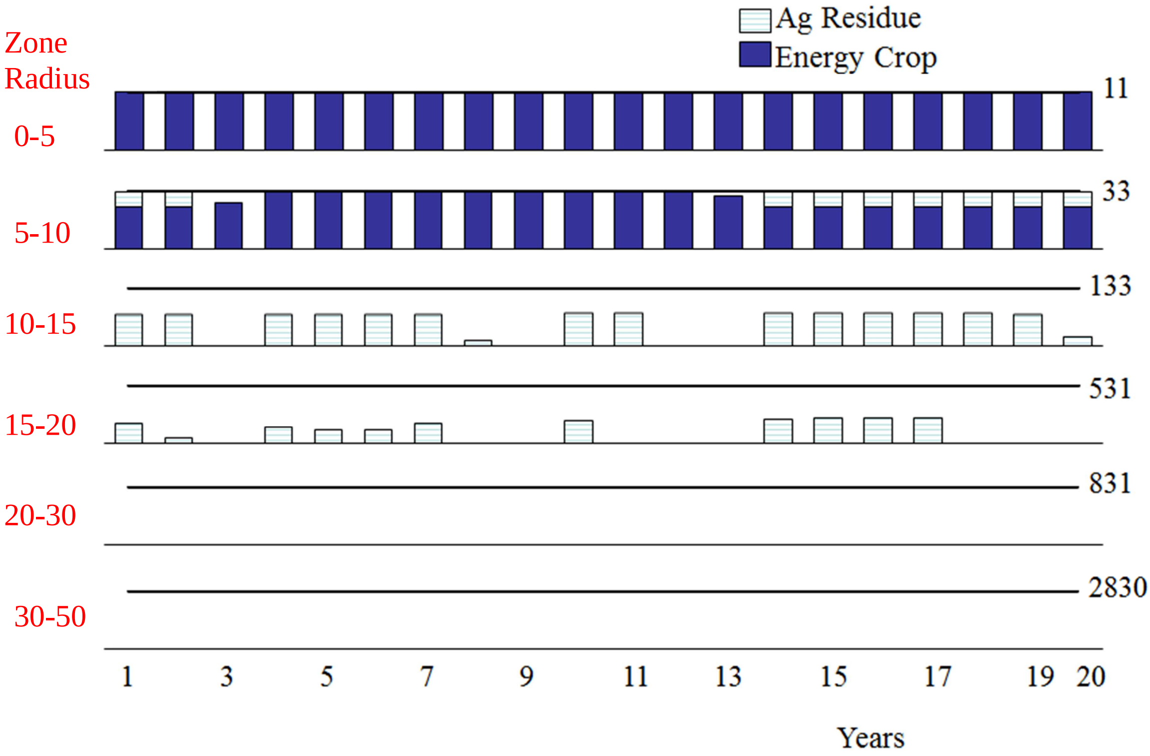
Figure 4.4: Spatial and temporal distribution of harvest shed – Scenario A (000 ac)*



* Even though the bars in figure 4.2 and 4.3 look the same, note that the acreage (denoted by the number on the right) is significantly different across the zones.

The results show an interesting pattern of spatial distribution of feedstocks. All available area is allotted to only one of the two feedstocks within a 10 mile radius (zones z_1 and z_2). This appears like a corner solution within each zone . However, when the entire harvest shed is considered, the solution is in fact an interior solution. The harvest shed includes both energy crops and agricultural residues within 5-15 radius (zones z_2 or z_3) but during different years. The major implication of this result is that optimal biomass supply varies not only spatially but also temporally. The answer for the question 'which feedstocks would feature in the interior solution?' is simple and intuitive – the feedstock that has lower delivery costs (sum of all cost components explained above) would appear as part of the

Figure 4.5: Spatial and temporal distribution of harvest shed – Scenario B (000 ac)



optimal feedstock portfolio – such a cost comparison and trade-off of land acreages to either feedstock occurs in fields 10-20 mile radius around the biorefinery (zones z_3 or z_4).

Substitution of energy crops with agricultural residues becomes more apparent (in the initial and final years) in scenario B. The higher proportion of energy crops in scenario B show that staggered harvesting is a preferred characteristic while developing feedstock portfolios since they help reduce costs and storage requirements. In spite of lower material costs, the proportion of agricultural crops is low due to lower yields per acre and inability to extend harvest into winter months.

Shadow Prices

The land acreage constraints are binding only in fields closer to the biorefinery i.e. within 0-15 mile radius around the biorefinery. That is, the biorefineries could reduce

Figure 4.6: Price premiums paid for cellulosic biomass by zone and year – Scenario A

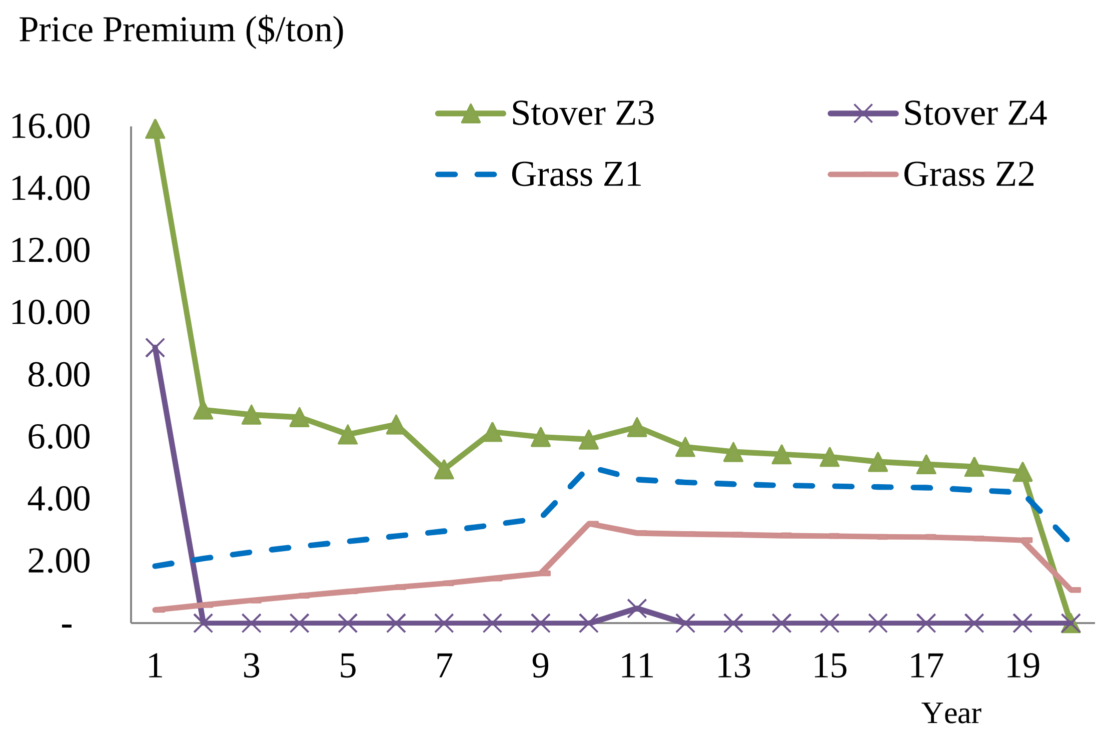
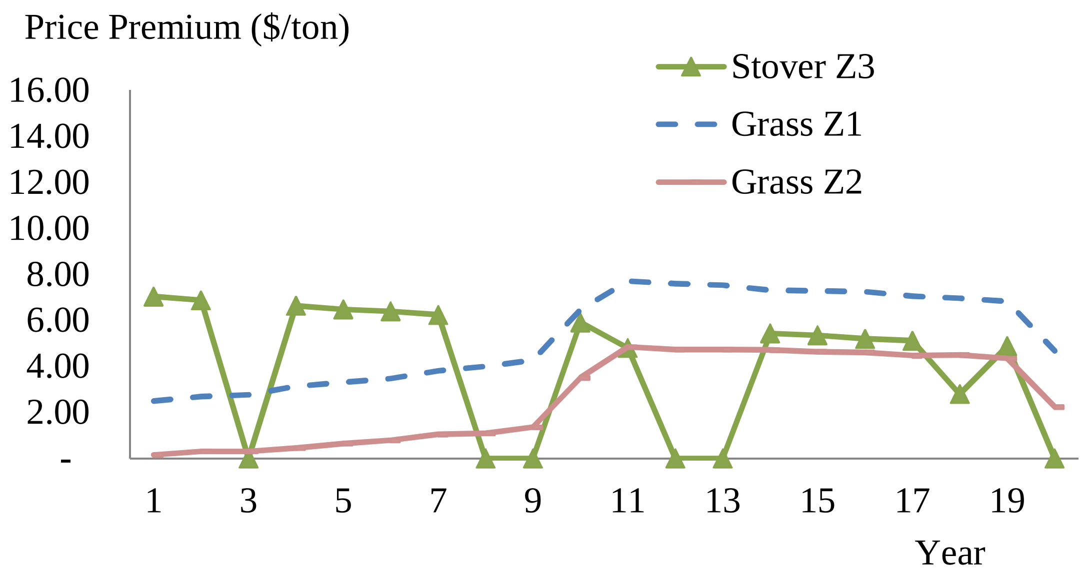


Figure 4.7: Price premiums paid for cellulosic biomass by zone and year – Scenario B



biomass raw material costs if more acres were to become available within this radius. Expanding the harvest shed area by a few acres is equivalent to relaxing the constraints that are binding. The biorefinery would be indifferent between ‘expanding the acreage by one more acre by paying a premium’ that is equal to cost savings not exceeding the shadow prices and ‘sourcing biomass from a field farther from the biorefinery.’ See figures 4.6 and 4.7 for the shadow prices of binding land constraints in scenarios A and B respectively. The price premiums (dollars per ton) are obtained by dividing the shadow price (in dollars per acre) by the amount of biomass harvested from one acre of harvest shed with any one of the feedstocks (tons). In case of agricultural residues, the yield per acre is relatively simple at 1.25 tons per acre. In case of energy crops, the biomass yield from one acre would be 84 tons per acre (3.3 tons per acre in year 1; 6.7 tons per acre in year 2; 10 tons per acre in years 3 through 7; 8 tons per acre in years 8, 9 and 10).

The shadow prices are a result of land constraints of the model; they are interpreted as the maximum amount of price premium payable for either feedstock over the estimated material prices. The shadow prices for agricultural residues are generally higher than that of energy crops. That is, a higher premium could be paid for agricultural residues until the delivered costs of both feedstocks become equal, at the margin.[26] In scenario A, the biorefinery could pay a premium ranging from $5-16 per ton of agricultural residues and $1-2 per ton of energy crops (figure 4.6). These premiums are warranted only for feedstocks grown closer to the biorefinery: 0-10 mile radius for energy crops and 10-20 mile radius for agricultural residues. The premiums decline with increasing distance from the biorefinery because of the interplay of increasing transport costs and varying density of

[26] A larger premium for agricultural residues would indirectly result in a larger output of feedgrains as well.

biomass (tons per square mile). The shadow prices for agricultural residues are higher in the initial years but decline gradually when larger quantities of energy crops become available. On the other hand, the shadow prices for energy crops increase over time as the proportion of energy crop biomass increases.

These shadow price results hold true for both scenarios A and B (figures 4.4 and 4.5). The main difference is with the dollar amounts of shadow prices. Energy crops command a higher price premium in scenario B because of the benefits of staggered harvesting. The shadow prices are choppier for agricultural residues in scenario B, because the reliance on agricultural residues in general decreases in scenario B where energy crop become more preferable.

4.6 Sensitivity Analysis

This section focuses on the impacts of relaxing the parametric assumptions on the proportion of energy crops and cost of cellulosic biomass raw materials. All results pertain to staggered harvesting in scenario B. Table 4.7 presents the proportion of energy crops under different material cost (CM): $30, 33, 36, and 39 per ton of energy crops and $22, 24.2, 26.4, and 28.6 per ton of agricultural residues. These values correspond to 10%-30% increase in their respective material costs. Consider the ratio of material costs: CM_g divided by CM_s. An increase in this ratio corresponds to energy crops becoming more expensive than agricultural residues (moving along a column from top to bottom). When this relative price ratio (CM_g / CM_s) increased, the proportion of energy crops decreased. The rate of substitution of agricultural residues for energy crops differed with the absolute values of material costs. For instance, the substitution was at a faster rate when the material cost of agricultural residues was lower.

Table 4.7: Proportion of energy crops at different material costs (percentage) – Scenario B

	Agricultural Residues ($/ton)			
	22	**24.2**	**26.4**	**28.6**
Energy crops ($/ton)	**percentages**			
30	72.9	74	80	81
33	67	71	74	81
36	56	64	70	73
39	48	51	64	70

To illustrate, consider the case where the material costs of agricultural residue are $22/ton and $28.60/ton. In the first case, when the energy crop material costs increased by 30%, the proportion of energy crops decreased from 72.9% to 48% (by 24% - first column in table 4.7). In the second case, for the same increase in energy crop prices, the proportion of energy crops decreased from 81% to 70% (only by 11% - last column). These results show that the proportion of any feedstock and its substitution depends on both absolute and relative costs of delivering alternative feedstocks. The ratio of material costs remain same along the leading diagonal cells (i.e. same relative price ratio, highlighted by grey background in table 4.7), the proportion of energy crops was relatively stable. Table 4.8 presents the biomass raw material costs per annual gallon of biofuel when the material costs of energy crops and agricultural resides increase by 10% to 30%. The raw material costs range between 60 and 70 cents per gallon of cellulosic ethanol and remain in the ballpark of estimates from previous studies.

Table 4.8: Cellulosic biomass raw material cost (cents per gallon) – Scenario B

	Agricultural Residues ($/ton)			
	22	**24.2**	**26.4**	**28.6**
Energy crops ($/ton)	**cents per gallon**			
30	60.6	61	62	62
33	63	64	64	65
36	65	66	67	68
39	67	68	69	70

Table 4.9 presents the impacts of greenhouse gas prices on optimal feedstock portfolio. When the GHG prices are increased from $15 to $50 per ton of carbon dioxide equivalent, the changes in feedstock mix are only minimal. The proportion of energy crops decreased slightly from 73% to 69%. Hence, GHG emissions do not seem to be a major factor determining the optimal feedstock mix or the proportion of energy crops. The optimal biomass portfolio may not vary with revenues from emissions markets or the lack of it. The differences in environmental benefits across energy crops and agricultural residues may not be sufficient enough to warrant an alternative feedstock composition.

Table 4.9: Impact of higher greenhouse gas prices on optimal feedstock portfolio – Scenario B

Technology	GHG Price ($/ton)	Proportion of energy crops (percentage)	Biomass raw material cost (cents per gallon)
Fermentation	**15**	72.9	60.6
	25	70.7	61.1
	50	69.0	62.3

Table 4.10 presents the changes in energy crop proportion with an increase in the land acreage available to source either feedstock. The results are intuitive. An increase in the acreage of marginal lands increases the proportion of energy crops (along the columns from top to bottom); an increase in the acreage of prime croplands decreases the proportion of energy crops (along the rows from left to right). In either case, the proportion of energy crops stayed relatively high at 70% or more. These results reinforce that biorefineries

would prefer a higher proportion of energy crops as part of their feedstock portfolios, in spite of higher material costs (or production costs). The advantages of energy crops include higher yields (tons per acre) and ability to harvest in a staggered manner play a crucial role in making them an attractive source of feedstock for the biorefineries.

Table 4.10: Proportion of energy crops under different land availability (percentage) – Scenario B

Prime + Marginal cropland supplying energy crops	Prime cropland supplying agricultural residues		
	5% of geographic area	10% of geographic area	15% of geographic area
14% of geographic area	78.6	72.0	NA
22% of geographic area	80.6	72.9	71.2
30% of geographic area	81.9	77.2	74.2

4.7 Conclusions

Cellulosic biorefineries face a challenge in developing low cost biomaterial raw supplies including multiple feedstocks. The biorefineries use waste materials that do not have much competing uses currently. This gives them the opportunity to design the harvest shed or collection area that can reduce biomass procurement costs and ensure reliable supply. Particularly, the biorefineries need to decide how, where and how much of alternative feedstocks to be grown within the harvest shed. In this paper, I evaluate the spatial and temporal design of such a harvest shed that include multiple agricultural feedstocks such as perennial energy crops and annual agricultural residues.

I develop a cost minimization model for a Midwestern biorefinery that will use agricultural feedstocks such as agricultural residues and energy crops. The model is developed to estimate the demand for these two feedstocks from the biorefinery's perspective. The optimization model minimize the cumulative costs associated with feedstock production, harvest, transport, storage, seasonal, and any environmental costs of choosing a feedstock. The objective is to identify the criteria that affect the preference for annual versus perennial feedstocks. The choice between annual and perennial feedstocks is important because they impose significantly different restrictions and planning requirements for the biorefinery. The two feedstocks differ in terms of yield levels, yield pattern, cost of production, and GHG emissions.

The constraints facing the biorefinery include available land area for sourcing feedstock, suitability of those lands, and biomass quantity required for continuous functioning of the biorefinery. The biorefinery could face contractual inflexibilities with perennial feedstocks (energy crops) because the energy crop farmers would require long term contracts that ensure demand for all cellulosic biomass that do not have many alternative uses. There is flexibility in harvesting or not harvesting agricultural residues because the revenues from agricultural residues are only secondary compared to the primary output of feedgrains. The biorefinery has to choose the acreage where energy crop and agricultural residues are planted. The transport costs, seasonal costs and environmental costs are modeled endogenous where they depend on the acreage decision variables. The spatial patterns around the biorefinery and temporal decisions are included in the optimization model.

The model parameters are calibrated for a case study location in Hugoton, KS where Abengoa Bioenergy is constructing its cellulosic biorefinery. The feedstock procurement decisions are modeled using one representative annual feedstock (corn stover) and one perennial feedstock (miscanthus). For the case study, the energy crops are assumed to supply biomass over 10 years. The feedstock harvest shed is divided into six concentric circular zones with outer radii of 5, 10, 15, 20, 30 and 50 miles. The agricultural residues are estimated to be harvested from prime cropland extending up to 12% of geographic area around the biorefinery. The energy crops are assumed to be harvested from either prime croplands (12%) or marginal croplands (10% of geographic area). The objective of the model is to minimize the cumulative discounted biomass procurement cost over the 20 year productive period of the biorefinery. The optimization results show that the biomass raw material cost would range from $0.60 to $0.70 per annual gallon of cellulosic biofuel. The energy crops are found to be preferred over the agricultural residues. The proportion of energy crop biomass ranged from 70-80% of total cellulosic biomass quantity used over 20 year time period. Although energy crops are more expensive and they impose contractual limitations on biorefineries, the benefits of energy crops' higher density (up to 10 tons per acre per year at its maximum production level) weighed in their favor. The energy crops are preferably grown within a 10 mile radius around the biorefinery. Beyond that radius, it would be cheaper to harvest agricultural residues than growing energy crops. These results are robust to many parametric assumptions including the land area available to harvest either feedstock.

The temporal pattern of harvest shed suggests that agricultural residues would be used as buffer feedstock to meet where there is a shortage of energy crop biomass. Such shortages happen in the initial years and middle years when the energy crops are being established or reestablished. The proportion of energy crops increased when they can offer other benefits such as extended harvest into winter seasons. Any feedstock that expands the harvest shed could ideally be part of the biomass raw material portfolio for the biorefinery. The shadow prices for the binding land constraints show that biorefineries could pay up to $16 per ton of additional agricultural residues in certain years depending on the location.

This model presents shadow prices for binding land acreage constraints that can be interpreted as the upper bound of price premiums payable to either feedstock. The shadow prices declined for agricultural residues over time; in contrast, the shadow prices for energy crops grew over time from $2-8 per ton. The shadow prices declined as the fields are located farther from the biorefinery. The environmental costs (due to GHG emissions in feedstock cultivation, harvest and transport) associated with energy crops are not found to be substantial to cause a change in the optimal biomass portfolio of the biorefinery.

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