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SWITCHGRASS BIOMASS TO ETHANOL PRODUCTION ECONOMICS: FIELD TO FUEL APPROACH

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SWITCHGRASS BIOMASS TO ETHANOL

PRODUCTION ECONOMICS: FIELD

TO FUEL APPROACH

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LIST OF SYMBOLS

Member Elements

Index	Description
M	Set of month: { Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb, Mar}
J	Set of prospective biorefinery locations: j = {Canadian, Garfield, Okmulgee, Payne, Pontotoc, Washington}
S	Set of plant sizes: s = {Small, Medium, Large}
I	Set of biomass source counties: i = {57 counties in Oklahoma}
L	Set of land category: l = {Crop land, Improved pasture land}
FT	Set of facilities. In this case, ft = {Processing facility, Storage facility}

Model Parameters

Parameter	Description
ρ^E	Price per unit of ethanol
λ_l	Cost of producing switchgrass on land *l* excluding cost of fertilizer
α_m	Cost of applied nitrogen by month *m*
γ_m	Cost of applied P_2O_5 by month *m*
Γ	Cost of storing of switchgrass biomass in the field
τ_{ij}	Round-trip cost of transporting a ton of switchgrass biomass from county *i* to biorefinery location *j*
ω	Annual cost of a harvest unit for cutting
ϖ	Annual cost of a harvest unit for raking-baling-stacking
θ_i	Proportion of switchgrass which is usable in-field storage in a month later at production region *i*
μ^E	Quantity of ethanol produced from a ton of switchgrass biomass
BP_{il}	Proportion of land *l* in county *i* available for harvesting switchgrass biomass for biorefinery use
$LAND_{il}$	Total acres of land producing switchgrass in county *i* by land categories *l*
YAD_m	Yield adjustment factor for switchgrass if harvested in month *m*
$BYLD_i$	Biomass yield (tons/acre/year) of switchgrass of land *l* at county *i*
$OMC_{s,ft}$	Operating and maintenance cost of the plant for facility of size s type *ft* made once in year 0
$AFC_{s,ft}$	Investment cost of the plant for facility of size s type *ft* made once in year 0

Model Parameters

Parameter	Description
PVAF	Present value of annuity factor, where the annuity factor is the annual net benefit for the ethanol production industry
t	Plant useful life (20 years)
r	Market interest rate (15%)
$CAPHUC_{im}$	Capacity of harvest unit for cutting in month *m* at county *i*
$CAPHUB_{im}$	Capacity of harvest unit for raking-baling-stacking in month *m* at county *i*
CAP_S	Processing facility capacity associated with plant size *s* (gallons of ethanol per month)
CAS_S	Biomass storage facility capacity associated with plant size *s* (tons of switchgrass biomass)

Descriptions of Variables

Variable	Description
NPV	Net present value of the biorefinery system
Q^{E}_{msj}	Quantity of ethanol produced in month *m* by a biorefinery of size *s* at location *j*
A_{iml}	Acres of switchgrass harvested in county *i* in month *m* by land category *l*
XSP_{im}	Tons of biomass harvested in month *m* and stored in county *i*
XST_{ijsm}	Tons of biomass transported in month *m* from county *i* to a biorefinery of size *s* at location *j*
HUC	Integer variable representing the total number of cutting harvest units used
HUB	Integer variable representing the total number of raking-baling-stacking harvest units used
XS_{im}	Tons of switchgrass biomass harvested in county *i* in month *m*
XSS_{im}	Tons of switchgrass biomass stored in source county *i* in month *m*
XSN_{im}	Tons of biomass removed from storage in county *i* in month *m*
$XShuc_{im}$	Proportion of a harvest unit for cutting used in county *i* in month *m*
$XShub_{im}$	Proportion of a harvest unit for raking-baling-stacking used in county *i* in month *m*
XPP_{jsm}	Tons of switchgrass processed by a plant of size *s* at plant location *j* in month *m*
β_{js}	A binary variable associated with biorefinery size *s* at location *j*

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

Table Page

Table Page

LIST OF FIGURES

Figure Page

CHAPTER I

SWITCHGRASS YIELD RESPONSE TO NITROGEN FERTILIZATION AND COST TO PRODUCE SWITCHGRASS BIOMASS DEPENDING ON HARVEST TIMING

Abstract

Biorefineries that expect to operate continuously throughout the year will require a steady flow of huge quantities of potential biomass feedstock including crop residues, wood waste and dedicated energy crops. Switchgrass has been proposed as a dedicated energy crop. Harvest constitutes a major cost component of feedstock delivered cost. The number of harvest machines required to support a biorefinery depends on the length of the harvest window. Extending the harvest window to take advantage of reduction in harvest machinery investment costs has important biological consequences. Both harvestable biomass yield and fertilizer requirements differ depending on time of harvest. The objective of the research reported in this paper is to determine switchgrass yield response to nitrogen fertilizer for a single annual harvest in July and also for a single annual harvest in October. The estimated response functions will be used to determine the cost to produce a ton of biomass feedstock with the optimal level of nitrogen that maximizes profit for both harvest times. Data were obtained from a field experiment conducted at the Oklahoma State University Agronomy Research Station in

Stillwater, OK that tested both a July harvest and an October harvest with four levels of nitrogen. Data were estimated using several functional forms. Based on statistical criteria, linear response plateau functional forms were selected to characterize both the July harvest and the October harvest response functions. The July harvest plateau yield of 4.36 tons per acre was achieved with an estimated annual nitrogen fertilizer application of 80 pounds per acre based on the field experiment done in Stillwater, OK. The October harvest plateau yield of 5.49 tons per acre was achieved with an estimated annual nitrogen fertilizer application of 63 pounds per acre. With conventional rates for hiring custom farm machinery operations, estimated farm gate production costs were $60 per ton for the July harvest and $50 per ton for the October harvest.

Introduction

Switchgrass (*Panicum virgatum*) is a perennial warm season grass native to North America. It has been researched as a renewable bioenergy crop since the mid-1980s. Economic and environmental assessments by Oak Ridge National Laboratory's Biofuels Feedstock Development Program identified switchgrass as a model energy crop species in 1990 (Wright, 2007). Reasons cited for the selection of switchgrass are that it is a versatile and adaptable plant; can grow and even thrive in many weather conditions, lengths of growing seasons, soil types, and land conditions; has low water and nutrient requirements and has positive environmental attributes (Wright, 2007). The U.S. Energy Independence and Security Act of 2007 (EISA) included a provision that by 2022, 36 billion gallons of biofuel be produced annually including 16 billion gallons of cellulosic biofuels. Biomass from dedicated energy crops such as switchgrass is expected to be required to provide some of the feedstock requirements to fulfill the EISA cellulosic biofuels goal.

Research and development is ongoing in an attempt to develop environmentally sound and economically competitive methods to generate ethanol from cellulosic biomass. The United States Environmental Protection Agency (USEPA) has identified six different methods for producing ethanol from cellulose (biochemical enzymatic hydrolysis; thermochemical/catalytic; thermochemical/biochemical; strong acid hydrolysis; dilute acid, steam explosion; consolidated hydrolysis and fermentation) (USEPA 2010, p. 115). A biorefinery that expects to operate continuously year round and produce ethanol based on any of these technologies will require a steady flow of huge quantities of cellulosic biomass.

Switchgrass harvested once per year after the first frost ensures the highest production of switchgrass biomass per acre (Kering et al. 2009). But harvesting all required feedstock during a relatively narrow harvest window will require a large investment in harvest machines and require that a substantial quantity of material be placed in storage. An extended harvest window strategy could be used to extend the harvest season over as many months as possible. In Oklahoma, the harvest season may begin in July and extend through March. This system would require a smaller investment in harvest machines since harvest machines and harvest crews can be use over many months.

A cost efficient biorefinery would select the most cost efficient harvest strategy. But it is expected that biomass yield from stands harvested in October (after the first frost) is greater than stands harvested in July (before the plant is matured) and it is also expected that nitrogen requirements are expected to vary based on the time of harvest (McLaughlin and Kszos 2005). Previous studies have reported that seasonal time of harvest affects biomass yield (Adler et al. 2006; Vogel et al. 2002; Sanderson, Read and Reed 1999). Biomass yield is lower from stands harvested in mid-season and protein (nitrogen) levels are relatively high in grasses cut in mid-season (Haque, Epplin, and Taliaferro 2009). Late in the growing season, nitrogen translocates from the above ground foliage to the plant's crown and rhizomes. If harvest is delayed until after the first frost and the initiation of senescence, biomass yield will be maximized and nitrogen will have translocated, which reduces the quantity of nitrogen fertilizer needed for biomass production in subsequent years (Kering et al. 2009; Adler et al. 2006; Vogel et al. 2002; Reynolds, Walker and Kirchner 2000; Madakadze et al. 1999; Sanderson, Read and Reed 1999). Hence, a prerequisite for determining the most cost-efficient harvest strategy is to determine switchgrass yield response to nitrogen based on time of harvest. Information on expected yield and nitrogen requirement for harvesting once per year in July or once per year in October would help to estimate switchgrass establishment, production and maintenance cost depending on month of harvest.

Several studies have been conducted to test switchgrass biomass yield response to nitrogen (Muir et al. 2001; Vogel et al. 2002; Thomason et al. 2004; McLauglin and Kszos 2005; Fike et al. 2006a; Mulkey et al. 2006; Lemus et al. 2008). The results reported are based on stands harvested once per year (after the first frost and the initiation of senescence), two harvest per year (July and after the first frost), and three harvests per year (May, July and after the first frost). Mulkey et al. (2006) evaluated South Dakota switchgrass stands enrolled in, or managed similar to Conservation Reserve Program grasslands, and reported yields of 1.56 to 2.46 tons per acre in 2002 from one location. They found that nitrogen applied at 50 pounds per acre per year increased total biomass without affecting switchgrass persistence, but found no additional benefit of nitrogen applied at rates in excess of 50 pounds per acre per year. Muir et al. (2001) reported a yield of 10.04 tons per acre from nitrogen applications of 160 pounds per acre per year at Stephenville, TX. Vogel et al. (2002) found that, averaged over years, maximum biomass yields were obtained from 108 pounds of nitrogen per year per acre. Thomason et al. (2004) found that applying 0 pounds of nitrogen per acre and harvesting three times produced 7.54 tons per acre, while 400 pounds of nitrogen per acre with three harvests produced 8.03 tons per acre. Fike et al. (2006a) found that, for their region (North Carolina, Kentucky, Tennessee, Virginia, and West Virginia), harvesting lowland switchgrass cultivars twice per year produced only 8% more biomass than a single harvest.

None of these studies reported expected yield and nitrogen requirement based on one single annual harvest in July. Ball, Hoveland, and Lacefield (2002) reported that nitrogen concentrations in switchgrass forage ranged from 1.6 to 2.2 percent. Lemus, Parrish, and Wolfe (2009) found nitrogen concentrations for a switchgrass biomass crop ranged from 0.3 to 0.6 percent when harvested as a single crop in late fall. Less nitrogen has shown to be removed in the biomass in the late-fall harvest compared to a two-cut harvest (midsummer and late fall) because of translocation of nitrogen and other nutrients in late fall to the plant crown and root systems. This indicates that less nitrogen may be required for switchgrass production when the biomass is harvested in late fall (Fike et al. 2006b; Lemus, Parrish and Abaye 2008; USDA, NRCS 2009).

The objective of the research reported in this paper is to determine switchgrass yield response to nitrogen fertilizer for a single annual harvest in July and also for a single annual harvest in October. The estimated response functions will be used to determine the cost to produce a ton of biomass feedstock with the level of nitrogen that maximizes profit for both harvest times. This study differs from prior studies in several respects. First, to our knowledge, for the first time this study estimates switchgrass yield response to nitrogen depending on the month of harvest. Secondly, the study estimates the cost to produce a ton of switchgrass biomass feedstock based on a single harvest per year in July and compares this result with the result of single harvest per year in October.

Material and Methods

Field Experiment

Data were obtained from a field experiment conducted on switchgrass at the Oklahoma State University Agronomy Research Station in Stillwater (36°10′N, 97°5′W) on a Kirkland silt loam soil (fine, mixed, superactive, and thermic Udertic Paleustolls) under the supervision of Taliaferro (2007). The experimental design was a randomized complete block with a split-plot arrangement of treatments and four replications. The plots were 131 feet by 180 feet and separated by a 49 foot alley in the east-west direction and 66 feet in the north-south direction. Four nitrogen rates: 30, 60, 120, and 240 pounds per acre per year after the establishment year were assigned to the 33 feet by 180 feet subplots. Two switchgrass harvest levels (once and twice per year) were assigned to the 33 feet by 66 feet sub-subplots.

To ensure adequate pH, phosphorous (P_2O_5), and potassium (K_2O), soil testing was done in April of 2002. Switchgrass is adapted to nutrient-deficient soils, but agronomist recommend soil testing before planting to determine pH and availability of nutrients to confirm soil fertility. In May-June 2002, herbicide 2, 4-Dichlorophenoxyacetic acid (2-4-D) was applied at 1.5 pounds per acre across all plots. A clean seedbed was prepared, 30 pounds per acre nitrogen was applied across all plots and switchgrass was planted on July 22-23. Seeds (a selection from the variety Alamo) (six pounds per acre) were drilled into the prepared clean seedbed using a Brillion seeder. None of the plots were harvested in the establishment year (2002). Switchgrass harvest presenescence is not recommended in the establishment year in the region (Lawrence et al. 2006). Among the three rows that were planted, only the center row was harvested for calculation of biomass yield.

No herbicide or fertilizer other than nitrogen was applied in the second and subsequent years. Nitrogen, in the form of urea (46-0-0, N-P_2O_5-K_2O), was applied to the subplots at levels of 30, 60, 120, and 240 pounds per acre per year in years after the establishment year. The two harvest sub-subplots were harvested in July and after senescence in October. The single harvest sub-subplots were harvested in October. Plots were harvested in 2003, 2004, and 2005. For the one-harvest management, all nitrogen was applied at the beginning of the growing season in March. For the two-harvest management, nitrogen applications were equally split between March and after the first harvest in July.

To estimate biomass yield response to nitrogen for the post senescence harvest system, data from the plots that were harvested once per year in October were used. Data from four replications of nitrogen levels of 30, 60, 120 and 240 pounds per acre per year were available. To estimate biomass yield response to nitrogen for the July harvest system, yield from the July harvest of the plots that were harvested twice per year were used. Nitrogen application to these plots was split with the first half of the nitrogen applied at the beginning of the season in March and the second half after the first harvest in July. Hence, nitrogen levels of 15, 30, 60, and 120 were assumed and used to estimate the July response function.

Descriptive statistics of annual switchgrass yield from both harvest strategies are summarized in Table I-1. The total number of observation used to estimate both the July and the October functions was 48 (four levels of nitrogen x four replications x three years). Average annual switchgrass yield response to nitrogen fertilization is shown in Figures I-1 and I-2.

Establishment and Maintenance Budget

A standard enterprise budgeting procedure was used to estimate switchgrass establishment and biomass farm gate production costs (AAEA 2000). Cost to store and transport biomass was not estimated. One budget was prepared to estimate costs in the year of establishment (Table I-2). A second budget was constructed to estimate annual maintenance and harvesting costs for years after stands were established (Table I-3).

The establishment budget includes cost estimates for tillage operations used to prepare a seedbed. The budgeted tillage operations include plowing, disking twice, and cultipacking. State average custom operation rates were used to estimate the cost of field operations (Doye and Sahs 2009). Soil tests from the plots did not indicate a need for phosphorous or potassium fertilizers at the time of establishment, so other than cost of nitrogen no other fertilizer cost was included on the establishment budget. Seeding rates of six pounds per acre of pure live seed were budgeted for switchgrass. Regional average seed price of $7.00 per pound was used. The estimated stand life of switchgrass is ten years. The estimated establishment costs were amortized over ten years at a rate of seven percent. These estimates were included as costs in the annual maintenance and harvesting budget (Table I-3). The annual maintenance budgets also include the cost of fertilizer, fertilizer application, cost of harvest, and land rental. Fertilizer costs and operating capital were assumed to vary depend on level of fertilizer application.

The October harvest budgets (Table I-6) do not include costs for fertilizer other than nitrogen because prior research has found that through the natural growth cycle of perennial grasses, near the end of the growing season, nutrients including phosphorus and potassium translocate from the above ground parts of the plant to the below ground parts of the plant. Research has confirmed that if harvest of a perennial grass is delayed until after senescence, removal of above ground parts of the plant will not mine large quantities of phosphorus and potassium from the soil. Muir et al. (2001) reported that addition of phosphorus fertilizer did not change switchgrass biomass yield on soils with initially low phosphorus levels. Therefore, no phosphorus fertilizer is included on the October harvest budget. Oklahoma soils are naturally rich in potassium and fields that are monocropped to wheat in the region are not fertilized with potassium (Zang and McCary 2009).

Since a July harvest would remove material prior to translocation, phosphorus is included in the July harvest strategy budget (Table I-7). The maintenance budget for the

July harvest strategy includes 10 pounds of P_2O_5 per acre per year (Thomason 2004).

Budgeted harvest operations include mowing, raking, and baling into large (1,148 pounds dry matter) (AGCO Corporation 2010) rectangular solid bales. State average custom operation rates were used to estimate harvest costs (Doye and Sahs 2009). The number of bales produced and cost of baling are a function of yield. The land rental rate budgeted for cropland is $60 per acre per year. The average 2005-09 cropland cash rental for Oklahoma non-irrigated cropland ranged from $28-$31 per acre (USDA, NASS 2009). The assumptions of $60 per acre for cropland lease rates used in the study are made to account for the need to entice land owners to enter into a long-term lease that would be necessary for the perennial grass and to recognize that land lease rates in the vicinity of a biorefinery would increase in response to the plant’s existence.

Estimation of Response Functions and Selection Criterion

Response Functions

Optimal levels of nitrogen fertilizer can be determined by fitting statistical models to crop yield data collected from field experiments (Cerrato and Blackmer 1990; Belanger et al. 2000; Vogel et al. 2002). Several different functional forms are commonly used to estimate crop yield response to fertilizer. Cerrato and Blackmer (1990) reported that model selection is a major factor affecting which rates are identified as being optimal. A number of studies have used the polynomial functional form (in particular, the quadratic functional form) and concluded that this type of functional form is appropriate for describing crop yield response to nitrogen and predicting optimal nitrogen level (Belanger et al. 2000; Schmidt et al. 2002; Shen et al. 2003; Sayili and Akca 2004).

In addition, many researchers have used the linear response plateau functional form (LRP) and concluded that the LRP form is more appropriate for crop yield response to nitrogen than the quadratic form (QR) (Lanzer and Paris 1981; Grimm, Paris and Williams 1987; Frank, Beattie and Empleton 1990; Chambers and Lichtenberg 1996). A few studies of crop yield response to nitrogen have found that a quadratic response plateau (QRP) functional form produces a better fit than a QR functional form (Cerrato and Blackmer 1990; Bullock and Bullock 1994; Alivelu 2006). Based on these prior findings, three functional forms, QR, LRP, and QRP were specified for October and July harvest data.

Quadratic Response Function

The QR functional form is as follows:

$$Y_{it} = \beta_0 + \beta_1 N_t + \beta_2 N_t^2 + \upsilon_i + \varepsilon_{it} \qquad (1.1)$$

where Y_{it} is the switchgrass yield (tons per acre per year) for each treatment *t* for each year *i*, β_0 is the intercept and β_1 is the slope parameter to be estimated, β_2 is the quadratic parameter to be estimated, N_t is the amount of nitrogen applied (pounds per acre per year) to the switchgrass field for each treatment *t*, $\upsilon_i \sim Normal\ (0, \sigma_\upsilon^2)$ is an independently and identically distributed error term with mean zero, and variance σ_υ^2 to capture random year effect, $\varepsilon_{it} \sim Normal\ (0, \sigma_\epsilon^2)$ is an independently and identically distributed usual error term with mean zero and variance σ_ϵ^2, and σ_υ^2 and σ_ϵ^2 are independent of each other.

Linear Response Plateau

The LRP functional form is specified as:

(1.2) $$Y_{it} = min(\beta_0 + \beta_1 N_t,\ y_m) + \upsilon_i + \varepsilon_{it}$$

where Y_{it} is the switchgrass yield (tons per acre per year) for each treatment *t* for each year i, β_0 is the intercept, β_1 is the slope parameter to be estimated, N_t is the amount of nitrogen applied (pounds per acre) for each treatment *t*, y_m is the average plateau yield, υ_i ~*Normal (0,* σ_υ^2*)* is an independently and identically distributed error term with mean zero, and variance σ_υ^2 to capture random year effect, ε_{it} ~ *Normal (0,* σ_ϵ^2*)* is an independently and identically distributed usual error term with mean zero and variance σ_ϵ^2, and σ_υ^2 and σ_ϵ^2 are independent of each other.

Quadratic Response Plateau

A QRP functional form is specified as:

(1.3) $$Y_{it} = min(\beta_0 + \beta_1 N_t + \beta_2 N_t^2,\ y_m) + \upsilon_i + \varepsilon_{it}$$

where Y_{it} is the switchgrass yield (tons per acre per year) for each treatment *t* for each year i, β_0 is the intercept, β_1 is the slope parameter to be estimated, N_t is the amount of nitrogen applied (pounds per acre per year) to the switchgrass field for each treatment *t*, y_m is the average plateau yield, υ_i ~*Normal (0,* σ_υ^2*)* is an independently and identically distributed error term with mean zero, and variance σ_υ^2 to capture random year effect, ε_{it} ~ *Normal (0,* σ_ϵ^2*)* is an independently and identically distributed usual error term with mean zero and variance σ_ϵ^2, and σ_υ^2 and σ_ϵ^2 are independent of each other.

Model Selection Criterion

Several selection criteria have been proposed to enable testing of the relative performance of functional forms to best fit the data. The Akaike information criterion (AIC) and the Bayesian information criterion (BIC) are popular tests that can be used to compare different nonlinear (statistical models in which both fixed and random effects enter nonlinearly) mixed models (Akaike 1974; Schwarz 1978; Wolfinger 1999). But these criteria do not take into account significance levels when selecting the best fitting model (Moffitt 2002).

The Likelihood Dominance Criterion (LDC) can be used to choose between non-nested models (QR and LRP) (Pollak and Wales 1991). The LDC compares the estimated log-likelihood ratio to critical points of the chi-square distribution, with adjustments for differences in the number of parameters, and considers significance levels of estimated parameters (Pollak and Wales 1991; Moffitt 2002). The most suitable functional form between nested models (QR and QRP; LRP and QRP) was chosen based on the Likelihood Ratio Test (LR). The LR test is of the ratio of the values of two likelihood functions from the restricted and the unrestricted models. The calculated LR test statistics follows a chi-square distribution.

Model Estimation

QR, LRP, and QRP models were estimated using the NLMIXED procedure in SAS (SAS Inst., 2003). "The NLMIXED procedure fits nonlinear mixed models in which both fixed and random effects are permitted to have a nonlinear relationship to the response variable" (Wolfinger 1999, p. 1). The default method of SAS for PROC

NLMIXED is adaptive Gaussian quadrature integration (SAS Inst., 2003) to approximate the likelihood function integrals as described by Pinheiro and Bates (1995). Trust region (TRUREG) optimization technique was used to maximize the likelihood functions (SAS Inst., 2003). Separate models were estimated for the data collected from the October harvest and the July harvest. The dependent variable is switchgrass yield (tons per acre per year) and the independent variable is nitrogen and years included as random variables. Model specification test were conducted for both data sets. The D'Agostino-Pearson K^2 test (Omnibus test) was performed to test for normality. The D'Agostino-Pearson K^2 test can detect deviations from normality due to either skewness or kurtosis (D'Agostino, Belanger, and D'Agostino, Jr. 1990). The LR tests were conducted to test for heteroskedasticity based on the log likelihood value obtained from the restricted and unrestricted models. The test statistics follow a chi-square distribution with degrees of freedom equal to the number of imposed restrictions.

Results

The D'Agostino -Pearson K^2 test (Omnibus test) failed to reject normality for both data sets ($\alpha = 0.01$). The LR test failed to reject the null hypothesis of homoskedasticity. Estimated parameters for the QR, LRP, and QRP models for the October harvest data are reported in Table I-4.

Based on the LDC (Pollak and Wales, 1991) and LR test, the LRP model was selected and used to conduct economic analysis for the October harvest strategy. The estimated maximum -2 log likelihood value for the QR model is 152.6 and LRP model is 135.2. Both models have same number of parameters ($n = 5$). Hypothesis testing on model functional form according to the LDC ranking favors the LRP model over the QR for October harvest data. In addition, estimated maximum -2 log likelihood value for the QRP model is 156.8. Hypothesis testing on model functional form according to the LR test favors the LRP over the QRP and QR over the QRP model. This result is consistent with crop yield response to nitrogen fertilizer findings reported by others (Lanzer and Paris 1981; Grimm, Paris and Williams 1987; Frank, Beattie and Empleton 1990; Chambers and Lichtenberg 1996). The illustration in Figure I-1, supports the finding that the LRP fits the data better than the QR and QRP.

Mean parameter estimates for nitrogen rates and variance parameter of error term of the LRP functions are statistically significant at the 10% level. Based on the LRP, the expected plateau switchgrass yield is about 5.49 tons per acre per year and the threshold level of nitrogen is 63 pounds per acre per year for fields that are harvested in October. This result is consistent with previous findings of switchgrass biomass yield response to nitrogen fertilizer if switchgrass is harvested once per year after the first frost (Sanderson, Read and Reed 1999; Vogel et al. 2002; Mulkey, Owens and Lee 2006; Fike et al. 2006a; Lemus et al. 2008). These studies have reported switchgrass biomass yield ranges from 2.43 to 5.62 tons per acre per year and the recommended nitrogen fertilization rate is 50-108 pounds per acre per year.

Estimated parameters from the QR, LRP, and QRP models when fitted to the July harvest data are reported in Table I-5. The estimated maximum -2 log likelihood value for the QR (89.1), LRP (88.6), and QRP (88.4) are very similar. However, based on the LDC ranking, the LRP functional form is favored over the QR functional form and based on LR test the LRP form is favored over the QR form but the QRP form is slightly favored over the LRP. But the parameter estimate of the QRP quadratic coefficient is slightly positive indicating increasing returns over the nitrogen range from zero to the plateau. No support for this finding exists in the literature. Since the estimated nitrogen level at the estimated plateau yield level differed by only seven pounds per acre between the QRP and the LRP, results from the LRP model were used to conduct economic analysis for the July harvest strategy. Based on the LRP, the expected plateau switchgrass yield is about 4.36 tons per acre per year and the threshold level of nitrogen is 80 pounds per acre per year for fields that are harvested in July (Figure 2). All mean parameter estimates for the LRP function are statistically significant at the 5% level.

Determining Profit-Maximizing Level of the Input

With a LRP function, equation (2) will exhibit constant positive marginal product when $y_m > \beta_0 + \beta_1 N_t$. The input-output price ratio (price of nitrogen to price of biomass ratio) will matter in choosing the profit maximizing level of the nitrogen (N*). The profit maximizing producer will optimally apply no input ($N = 0$) if the value of the marginal product (VMP) is equal to or less than marginal factor cost (MFC). However, if VMP > MFC, it is beneficial to apply the quantity of N required to reach the plateau yield. Increasing N beyond the level to reach y_m will generate zero marginal returns. Therefore, with the LRP function, the profit maximizing nitrogen level (N*) would either be the level required to reach the plateau (*Np*) or zero:

(1.4) $$N^* = \begin{cases} N_P & \text{if VMP} > MFC \\ 0 & \text{otherwise} \end{cases}$$

The profit maximizing N level for an October harvest is either zero or 63 pounds per acre. With a biomass price of \$40 per ton, the VMP of nitrogen is (\$40 * 0.04655) \$1.86 per pound. The optimal choice of nitrogen for a profit maximizing producer for

October harvest remains at 63 pounds per acre as long as the price of nitrogen is above zero and is less than the VMP of $1.86 per pound. In addition, the optimum level of nitrogen for LRP of July harvest data is either zero or 80 pounds per acre. With biomass price assumed to be $40 per ton, the VMP of nitrogen is ($40 * 0.03014) $1.21 per pound. The optimal nitrogen level for a profit maximizing producer for July harvest remains at 80 pounds per acre as long as the price of nitrogen is above zero and is less than the VMP of $1.21 per pound. The average price of nitrogen from year 2000-2009 ranged from $0.22 per pound to $0.60 per pound (USDA, ERS 200) which is less than the estimated VMP of nitrogen of $1.21 and $1.86 for July and October harvests, respectively. By these measures, applying the level of nitrogen required to achieve the plateau yield would be economically optimal.

Economic Analysis: Switchgrass Production Cost

Table I-6 includes estimates of the per acre cost to produce and harvest switchgrass for the October harvest system. The annual budget in Table I-6 reflects per-acre costs of $27.86 for establishment, $34.28 for nitrogen and nitrogen application, $60 for cropland rental, and $154.01 for harvest. For a yield of 5.49 tons per acre and an annual nitrogen fertilizer application of 63 pounds per acre, the estimated cost to produce and harvest one dry ton of switchgrass biomass is $50.30. Twelve percent of the estimated cost to produce and harvest a ton of switchgrass is for establishment, 22 percent for land rental, 12 percent for nitrogen, and 56 percent for harvesting. The cost of storing the biomass until required by the biorefinery and the cost of transporting the biomass from the field to the biorefinery are not included in these estimates.

This result is consistent with the result reported by Mooney et al. (2008). They found that switchgrass production costs fall within a range from $45 per ton to $70 per ton for a well-drained level upland environment to a poorly drained flood plain in which the switchgrass stand was slow to establish and which demonstrated lower overall yields. In addition, the cost estimation is lower than the estimated cost of production of biomass from switchgrass by Khanna, Dhungana and Clifton-Brown (2008) and Perrin et al. (2008). Khanna, Dhungana and Clifton-Brown (2008) estimated the cost of producing switchgrass in Illinois is about $78.12 per ton for an annualized yield of 2.58 tons per acre. Perrin et al. (2008) estimated farm-scale production cost of switchgrass for biomass for northern North Dakota to southern Nebraska. They estimated the cost to produce and harvest a ton of switchgrass biomass is $59.73 for a yield of 2.23 tons per acre.

Table I-7 includes estimates of the per acre cost to produce and harvest switchgrass for the July harvest system. The annual budget in Table I-7 reflects per acre costs of $27.86 for establishment, $47 for nitrogen, phosphorus and fertilizer application, $60 for cropland rental, and $125.19 for harvest. For a yield of 4.36 tons per acre and an annual nitrogen fertilizer application of 80 pounds per acre, the estimated cost to produce and harvest one dry ton of switchgrass biomass is $59.65. Eleven percent of the estimated cost to produce and harvest a ton of switchgrass is for establishment, 23 percent for land rental, 18 percent for nitrogen, and 48 percent for harvesting.

The cost per ton of biomass form an October harvest is less than the cost from a July harvest. Stands harvested in July required 80 pounds per acre of nitrogen and 10 pounds per acre phosphorus whereas stands harvested in October required only 63 pounds per acre of nitrogen. Additionally, the average yield from a July harvest is 4.36

compared to 5.49 tons per acre from the October harvest. Hence, farm gate costs per ton are lower if harvest is delayed until October relative to a July harvest.

Summary and Conclusion

The objective of the research reported in this paper was to determine switchgrass yield response to nitrogen fertilizer for a single annual harvest in July and also for a single annual harvest in October. For both harvest strategies, a Linear Response Plateau functional form was selected to represent biomass yield response to nitrogen. The estimated response functions were used to determine the cost to produce a ton of biomass feedstock with the estimated plateau yield level for both harvest strategies.

Switchgrass produced more biomass when harvest was delayed until after the first frost and the initiation of senescence (once per year in October) than if harvested before the plant is mature (once per year in July). Fields that are harvested in July are expected to require 80 pounds per acre of nitrogen to achieve the plateau yield of 4.36 tons per acre, whereas fields harvested in October are expected to require only 63 pounds per acre to achieve the plateau yield of 5.49 tons per acre. By these measures, fields that are harvested in July would require an additional 17 pounds per acre of nitrogen and produce 1.13 tons per acre less biomass.

The farm gate cost to produce and harvest a ton of switchgrass biomass is lower for an October harvest than for July harvest. For a yield of 4.36 tons per acre and an annual nitrogen fertilizer application of 80 pounds per acre, the estimated cost to produce and harvest one dry ton of switchgrass biomass in July is $59.65. And, for a yield of 5.49 tons per acre and an annual nitrogen fertilizer application of 63 pounds per acre, the estimated cost to produce and harvest one dry ton of switchgrass biomass in October is $50.30. Harvest cost comprises the largest component of the farm gate cost.

One shortcoming of this study was that the data used to estimate response functions for July were not obtained from plots that were only harvested once per year in July. Biomass yield of the first harvest (harvested in July) from plots that were harvested twice per year (once in July and once in October) were used to estimate the response function. Since only half of the nitrogen was applied at the beginning of the season in March and half was applied after the first harvest in July, nitrogen from the second application may have carried over into the subsequent season and affected biomass yield. In addition, the October removal of biomass from these plots may have influenced the yield of the subsequent July harvest. Another field experiment would need to be conducted to test the consequences of these limitations.

Another shortcoming is related to the location. The results and conclusions are based on field experiments conducted in Stillwater, OK. Switchgrass field experiments data from other Oklahoma counties are not available. However, other field experiments on switchgrass conducted in different counties would be required to test the consequences of these limitations.

Another shortcoming is related to the application of phosphorus. In the field trial, phosphorus was not applied since prior research has confirmed that through the natural growth cycle of perennial grasses, near the end of the growing season, nutrients including phosphorus and potassium, translocate from the above ground parts of the plant to the below ground parts of the plant and addition of phosphorus fertilizer will not change switchgrass biomass yield. Hence, harvesting in October does not require phosphorus but a July harvest would remove material prior to translocation, phosphorus fertilization was assumed to be required for the July harvest strategy. However, additional field research would be required to confirm this assumption.

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APPENDIX FOR CHAPTER I

Table I-1. Descriptive Statistics of Switchgrass Biomass Yield Data Collected from Field Experiments for July and October Harvests

Nitrogen (pounds/acre)	Mean	Minimum	Maximum	Std Dev
		July Harvest[a]		
15	2.44[b]	1.36	3.61	0.72
30	2.77	1.97	3.65	0.45
60	3.77	2.96	5.26	0.66
120	4.36	3.38	5.30	0.67
		October Harvest		
30	3.86[b]	2.50	5.09	0.70
60	5.36	3.74	6.47	0.84
120	5.41	3.84	6.45	0.81
240	5.51	4.48	6.92	0.75

[a] Data from the July harvest from plots that were harvested in both July and October.
[b] Average yield (dry tons per acre) over three years (2003, 2004, and 2005) and across four replications.

Table I-2. Estimated Switchgrass Establishment Costs ($/acre)

Item	Unit	Quantity	Price/unit ($)	Value ($/acre)
Machinery operation				
Tillage				
Moldboard plow	acre	1	15.93	15.93
Tandem disk	acre	2	10.47	20.94
Chemical and fertilizer application				
Spraying herbicide	acre	1	4.94	4.94
Applying nitrogen	acre	1	4.14	4.14
Planting				
Cultipack	acre	1	8.96	8.96
Seeder	acre	1	13.26	13.26
Operating input				
Switchgrass seed	lbs.	6	7.00	42.00
Herbicide (2,4-D)	pt.	1.5	1.90	2.85
Nitrogen	lbs.	30	0.46	13.80
Annual operating capital [a]	$	126.82 [a]	0.07	8.88
Land rental	acre	1	60.00	60.00
Total machinery, input and land rental cost	$			195.70
Establishment cost, amortized for 10 years at 7%	$		0.07	27.86

Table I-3. Estimated Annual Switchgrass Maintenance and Harvesting Costs ($/acre) [a]

Items	Unit	Quantity	Price per unit ($)	Value ($/acre)
Establishment cost amortized over 10 years at 7%	$			27.86
Fertilizer application	acre	1	4.14	4.14
Operating inputs				
Nitrogen	lbs.	variable [b]	variable	variable
P_2O_5	lbs	variable [c]	variable	variable
Annual operating capital	$	variable	variable	variable
Machinery operation				
Mowing	acre	1	10.11	10.11
Raking	acre	1	3.88	3.88
Harvesting (baling) 1,148 lb DM Rectangular bale	bale	1	14.64	variable
Land rental	acre	1	60	60.00
Total production cost				variable
Average harvested yield	ton			variable
Cost	$/ton			variable

[a] Machine operation costs obtained from Doye and Sahs (2009).
[b] Nitrogen application depends on harvest strategy.
[c] Phosphorus is budgeted for the July harvest strategy but not for the October harvest strategy.

Table I-4. Switchgrass Biomass Yield Response to Nitrogen for a Quadratic, a Linear Response Plateau, and a Quadratic Response Plateau Functional Form from Plots Harvested Once per Year in October

Variables	Quadratic	Linear Response Plateau	Quadratic Response Plateau
Intercept	2.3075* (0.5667)[b]	2.5353 (2.9850)	1.9797* (0.4708)
Nitrogen rate (lbs/acre)	0.05609** (0.008748)	0.04655* (0.01143)	0.07057** (0.01232)
Nitrogen squared	-0.00018** (0.000031)		-0.00024** (0.000044)
Plateau yield (tons/acre)		5.4871 (2.9417)	5.3824** (0.1767)
Level of nitrogen at maximum yield (lbs/acre)	155.80	63.41	106
The variance of the error term for random year effects	3.284E-9 (0.1727)	1.663E-8 (1.0915)	5.12E-12 (0.02063)
The variance of the usual error term	0.6738** (0.09791)	0.7033** (0.1139)	0.3727 (0.03967)
-2 Log likelihood	152.6	135.2	156.8

The dependent variable is switchgrass yield (dry tons per acre) from a single harvest in October.

[a] One, two, or three asterisks (*) indicate statistical significance at the 0.10, 0.05 or 0.01 level, respectively.

[b] Numbers in parentheses are standard errors.

Table I-5. Switchgrass Biomass Yield Response to Nitrogen for a Quadratic, a Linear Response Plateau, and a Quadratic Response Plateau Functional Form from the July Harvest of Plots Harvested Twice per Year, July and October

Variables	Quadratic	Linear Response Plateau	Quadratic Response Plateau
Intercept	1.7601** (0.2871)[b]	1.9396** (0.2184)	2.2178* (0.5847)
Nitrogen rate (lbs/acre)	0.04324* (0.01122)	0.03014** (0.005386)	0.01106 (0.03759)
Nitrogen squared	-0.00018 (0.000079)		0.000247 (0.000482)
Plateau yield (ton/acre)		4.3602** (0.1802)	4.3602*** (0.1799)
Level of nitrogen at maximum yield (lbs/acre)	120.11	80.3185	73.39
The variance of the error term for random year effects	0.005811 (0.02412)	0.006084 (0.02411)	0.006217 (0.02410)
The variance of the usual error term	0.3699* (0.07798)	0.3655** (0.07706)	0.3634** (0.07661)
-2 log likelihood	89.1	88.6	88.4

The dependent variable is switchgrass yield (dry tons per acre) from harvest in July.
[a] One, two, or three asterisks (*) indicate statistical significance at the 0.10, 0.05 or 0.01 level, respectively.
[b] Numbers in parentheses are standard errors.

Table I-6. Estimated Annual Maintenance and Harvesting Costs for Established Stands of Switchgrass Harvested Once per Year in October ($/acre)

Items	Unit	Quantity	Price per unit ($)	Value ($/acre)
Establishment cost amortized over 10 years at 7%	$			27.86
Fertilizer application	acre	1	4.14	4.14
Operating inputs				
Nitrogen	lbs.	63	0.46	28.98
Annual operating capital	$	16.56	0.07	1.16
Machinery operation				
Mowing	acre	1	10.11	10.11
Raking	acre	1	3.88	3.88
Harvesting (Baling) 1,148 lb DM Rectangular bale [a]	bale	1	14.64	140.02
Land rental	acre	1	60	60.00
Total production cost				276.15
Average harvested yield	ton	5.49		
Cost	$/ton		50.30	

[a] This size is budgeted based on the information provided by AGCO Corporation (2010).

Table I-7. Estimated Annual Maintenance and Harvesting Costs for Established Stands of Switchgrass Harvested Once per Year in July ($/acre)

Items	Unit	Quantity	Price per unit ($)	Value ($/acre)
Establishment cost amortized over 10 years at 7%	$			27.86
Fertilizer application	acre	1	4.14	4.14
Operating inputs				
Nitrogen	lbs.	80	0.46	36.80
P_2O_5	lbs	10	0.53	5.25
Annual operating capital	$	11.55	0.07	0.81
Machinery operation				
Mowing	acre	1	10.11	10.11
Raking	acre	1	3.88	3.88
Harvesting (baling) 1,148 lb DM Rectangular bale	bale	1	14.64	111.20
Land rental	acre	1	60	60.00
Total production cost				260.05
Average harvested yield	ton	4.36		
Cost	$/ton		59.65	

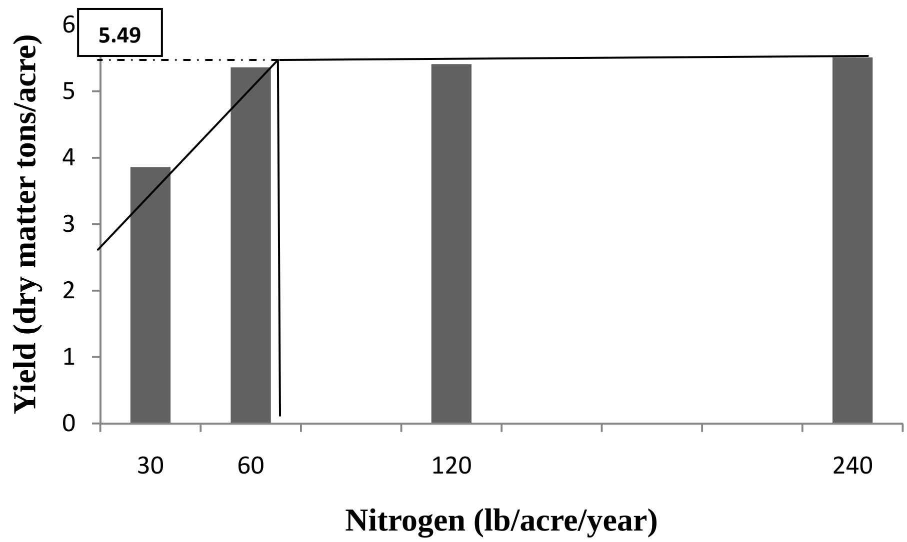

Figure I-1. Switchgrass biomass yield response to nitrogen fertilization if harvested once per year in October.

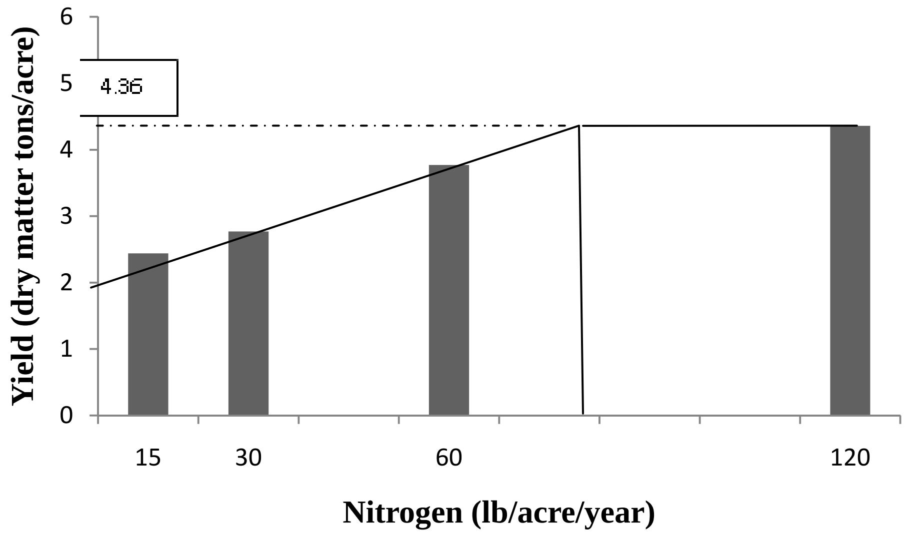

Figure I-2. Switchgrass biomass yield response to nitrogen fertilization if harvested once per year in July.

CHAPTER II

OPTIMAL SWITCHGRASS HARVEST STRATEGIES ACCOUNTING FOR YIELD AND NITROGEN REQUIREMENT DIFFERENCES BY MONTH OF HARVEST

Abstract

Year-round operation of a cellulosic biorefinery will require year-round delivery of feedstock. To obtain the maximum harvestable yield a dedicated energy crop such as switchgrass would be harvested in a relatively narrow window (September and October). However, in Oklahoma the switchgrass harvest window could extend from July through March. Extending switchgrass harvest over many months would require a smaller investment in harvest machines, but would result in a lower average harvestable yield per acre and would require more nitrogen fertilizer. The objective of this research is to determine the cost to deliver a ton of switchgrass biomass to an ethanol-conversion facility, optimally located in Oklahoma, which can process 2,000 dry tons per day. The results from a model that adopt an extended harvest window will be compared with the results from a model that restricts harvest to two months. The model accounts for differences in yield and nitrogen fertilizer requirements across harvest months. The data were incorporated into a multi-region, multi-period, monthly time-step, mixed integer mathematical programming model that was constructed to maximize the net present

value of the system. Based on the model results, the strategy of extending harvest over many months is economically preferable to a strategy of harvesting only in peak yield harvest months. Restricting harvest to a two-month harvest season would increase the cost to deliver feedstock by 23 percent.

Introduction

The U.S. Energy Independence and Security Act of 2007 (EISA) included a provision that by 2022, 36 billion gallons of biofuel be produced annually including 16 billion gallons of cellulosic biofuels. Biomass from dedicated energy crops such as switchgrass and crop residues is expected to provide most of the feedstock requirements to fulfill the EISA cellulosic biofuels goal. Given a switchgrass yield of three tons per acre and a conversion rate of 90 gallons per ton, a 50 million gallons per year biorefinery would require 185,000 acres for production of biomass. If the average yield was seven tons per acre, 79,300 acres would be required.

The economic viability of a switchgrass biorefinery will depend on the cost to produce, harvest, store, and deliver feedstock. Several studies have estimated costs for production, harvest, storage, and transportation of switchgrass biomass (Epplin 1996; Duffy 2007; Epplin et al. 2007; Khanna, Dhungana and Brown 2008; Mooney et al. 2008; Sokhansanj et al. 2009). These prior studies have reported considerable differences in production, harvest, storage, and transportation costs (table II-1). They found that harvest cost is an important component of the cost of switchgrass biorefinery processing and comprised 30-45% of the total delivered feedstock cost.

Epplin (1996) reported a switchgrass harvesting cost of $10.80 per dry ton and total delivery cost of $33.66 per dry ton for a biorefinery located in Oklahoma but he did not include storage cost. Duffy (2007) reported total delivered cost of $113.66 per ton for Iowa and harvest cost comprised 32 percent of the total delivered cost. Khanna, Dhungana, and Brown (2008) estimated the production, harvest, storage, and transportation costs of switchgrass biomass for a biorefinery located in Illinois and found that harvest cost of switchgrass was 35 percent of the total cost of all items considered. Mooney et al. (2008) estimated the production and harvest cost of switchgrass for Tennessee and found that harvesting cost constituted 46 percent of total delivered cost.

In Oklahoma, switchgrass may be harvested in mid-season as early as July. Biomass yield is lower from stands harvested in mid-season and protein (nitrogen) levels are relatively high in grasses cut in mid-season (Chapter I). Late in the growing season, nitrogen translocates from the above ground foliage to the plant's crown and rhizomes. If harvest is delayed until after the first frost and the initiation of senescence, biomass yield will be maximized and nitrogen will have translocated, which reduces the quantity of nitrogen fertilizer needed for biomass production in subsequent years (Madakadze et al. 1999; Sanderson, Read and Reed 1999; Reynolds, Walker and Kirchner 2000; Vogel et al., 2002; Adler et al. 2006; Kering et al. 2009).

Kering et al. (2009) found that, switchgrass harvested once after first frost ensures highest production of biomass in Oklahoma. Sanderson, Read, and Reed (1999) found that on their plots near Dallas, Texas, biomass yield was maximized with a single harvest in mid-September. Vogel et al. (2002) found that less nitrogen is needed if switchgrass is harvested for biomass after a killing frost. Reynolds, Walker and Kirchner (2000) found that the nitrogen concentration in plants was typically lowest in the fall harvest of a one-cut system. Similarly, Madakadze et al. (1999) concluded that switchgrass plant nitrogen concentration is different depending on harvest dates. Early cut material has higher nitrogen concentrations than late cut. Also, Jannasch, Duxbury and Samson (2001) reported that if switchgrass is left in the field after maturity for harvesting the following spring, there is a 30 percent reduction in biomass yield in Canada. Similarly, Adler et al. (2006) evaluated biomass yield and biofuel quality of switchgrass harvested in fall or spring and they reported a 40 percent reduction in yield using a delayed harvest in Pennsylvania.

Year-round operation of a biorefinery will require year-round delivery of feedstock but switchgrass cannot be harvested in every month. One alternative would be to harvest switchgrass during a relatively narrow window (September and October) when harvestable yield is greatest and store it until needed as with conventional grain crops such as corn. This system is expected to result in the largest harvestable yield per acre and minimal requirements for nitrogen fertilizer, but would require a relatively large investment in harvest machines and a large investment in storage. Another alternative would be to extend the harvest season over as many months as possible (July through March). This system would require a smaller investment in harvest machines since they could be used over many months. However, this system would result in a lower average harvestable yield per acre and would require more nitrogen fertilizer, less land for storage, and more land for growing switchgrass.

Previous studies have estimated switchgrass production, fertilization, harvest, storage, and transportation strategies that maximize the net present value of a cellulosic biorefinery system or that minimize the cost to deliver feedstock to an optimally located biorefinery (Tembo, Epplin, and Huhnke, 2003; Epplin et al., 2007; Mapemba et al., 2007; Mapemba et al., 2008; Hwang, 2007). They find that feedstock harvest cost is a key cost component and that the length of the harvest season matters.

Rather than assume a narrow harvest window, Tembo, Epplin, and Huhnke (2003), Hwang (2007), and Mapemba et al. (2008) assumed that switchgrass could be harvested in Oklahoma from July through February. They did not have precise information about switchgrass yield differences across months of harvest and assumed that the quantity of fertilizer required would not differ across harvest months. Results of more recent field trials enable estimates of yield differences and nitrogen requirement differences across harvest months (Chapter I). This information could be used to determine if a strategy of extending the harvest over many months is economically preferable to a strategy of harvesting only in peak harvest months. Maximization of net present value of a cellulosic biorefinery system that uses switchgrass feedstock requires an understanding of the many tradeoffs encountered when the length of the harvest window is changed.

Objective

The general objective of the paper is to determine the switchgrass production, fertilization, harvest, storage, and transportation strategy that would provide the least-cost flow of switchgrass biomass to a biorefinery located in Oklahoma that operates continuously throughout the year. The specific objectives include:

1) To determine the cost to deliver a ton of switchgrass biomass produced on cropland and/or improved pasture land to a biorefinery, optimally located in Oklahoma, which can process 2,000 dry tons per day.

2) To compare the results from a model that permits a harvest window from July through March with the results from a model that restricts harvest to September and October with the model accounting for differences in yield and nitrogen fertilizer requirements across harvest months.

3) To update the set of machines budgeted and update estimates of machinery costs for harvesting switchgrass (Thorsell et al. 2004; Hwang 2007).

This study differs from prior studies in several respects. First, data produced in a designed multiyear field trial were used to estimate switchgrass harvestable yield response to nitrogen fertilizer for alternative harvest months. Second, this study is the first attempt to account for differences in nitrogen requirements dependent on months of harvest for switchgrass. These data enable a comparison of the economic tradeoffs between a relatively narrow harvest season versus an extended harvest season. Third, for the first time, switchgrass production is modeled to compete for both improved pasture land and cropland. Since Oklahoma has 4.7 million acres in improved pasture land and switchgrass is a perennial grass that is naturally drought resistant and grows on marginal land, there is potential to grow switchgrass on improved pasture land. In addition, in Oklahoma, on average, cropland cash rental is less than pasture land cash rental.

Data Descriptions and Assumptions

Biomass Establishment and Maintenance

The study is based on the assumption that a biorefinery would depend entirely on switchgrass as a single feedstock. Data on expected switchgrass yield depending on month of harvest were obtained from Chapter I (from a field trial conducted at Stillwater, OK) and from expert opinion (Taliaferro 2000). In Chapter I, switchgrass biomass yield response to nitrogen fertilizer was estimated for July as well as October harvests. These yield estimates were combined with other data (figure II-1) (Graham, Allison and Becker 1996) and expert opinion (Taliaferro 2000) to produce yield estimates for each of 57 Oklahoma counties for each of nine harvest months. Table II-2 includes estimates of the proportion of potential switchgrass expected yield by harvest month. In Oklahoma, harvest season for switchgrass could begin as early as July and continue for an extended period, as late as March. However, harvests during April, May, or June are not expected since it is anticipated that harvest during these months would damage plant growth for subsequent years. Maximum expected yield is obtained by harvesting in either September or October. Expected yield from harvest in July is 79 percent of maximum. If switchgrass is left to stand in the field, dry matter losses of five percent per month are expected from November through March. This result is consistent with field loses from delayed harvests reported by Vogel et al. (2002).

Table II-2 also includes estimates of the level of nitrogen (pounds per acre) applied in the spring required to achieve the plateau yield depending on harvest month. For modeling purposes the price of nitrogen relative to the price of switchgrass is assumed to be at a level so the profit maximizing quantity of nitrogen is at the plateau point on the production surface. Fields that are harvested in July are expected to require 80 pounds per acre of nitrogen to achieve the plateau yield, whereas fields harvested during and between October and March are expected to require only 63 pounds per acre (Chapter I). It is also assumed that fields that are harvested during and between July and September are expected to require 10 pounds of phosphorus in the form of P_2O_5 per acre (Thomason 2004).

Potential Switchgrass Production Locations and Potential Plant Locations

The model includes 57 of Oklahoma's 77 counties as production regions. Tall grasses such as switchgrass are not common in the native prairies of the westernmost 20 counties of Oklahoma (Figure II-2). Field trials would be required to determine if pure stands of switchgrass would persist on the soils and in the climate of these counties (Wu, 2009; Kakani, 2009). Six potential biorefinery locations (Canadian, Garfield, Okmulgee, Payne, Pontotoc, and Washington counties) are included in the model. These locations were selected considering switchgrass biomass relative density and availability of road infrastructure.

Land Acquisition

In the model, switchgrass production is restricted to two land classes: cropland and improved pasture land. Data from the census of agriculture are used to determine existing acres of cropland and improved pasture (USDA 2002). The expected switchgrass yields in a given county for a given harvest month are assumed to be the same on improved pasture land as on cropland (Wu 2009; Kakani 2009). This assumption follows from the finding that switchgrass yield is limited more by available moisture and the length of the growing season than by soil quality (Wu 2009; Kakani 2009).

Restrictions are included in the model to limit switchgrass production in each county to no more than ten percent of the county's cropland and no more than ten percent of the county's improved pasture land. Another assumption is that the use of this cropland and improved pasture land can be acquired at a long-term lease rate of $60 and $40 per acre per year, respectively. The average 2005-09 cropland cash rental for Oklahoma non-irrigated cropland ranged from $28-$31 per acre, and the average 2005-09 pasture land cash rental for Oklahoma ranged from $8.50-$10.50 per acre (USDA, NASS 2009). The assumptions of $60 and $40 per acre for cropland and pasture land lease rates used in the study are made to account for the need to entice land owners to enter into a long-term lease that would be necessary for the perennial grass and to recognize that land lease rates in the vicinity of a biorefinery would increase in response to the plant's existence. Switchgrass production cost estimates are based on establishment and maintenance budgets prepared in Chapter I. The estimated establishment costs for switchgrass grown on cropland and improved pasture land of $195.70 and $175.70 per acre respectively are amortized at a rate of seven percent over ten years. The biorefinery is assumed to operate 350 days per year and require 2,000 dry tons of feedstock per operating day.

Harvesting Operations

The biomass integrated harvest unit concept was introduced by Thorsell et al. (2004) and modified by Hwang (2007). In this study the harvest unit concept was revised and used to determine the cost of switchgrass harvest machines. Expert opinion (AGCO Corporation 2010; ASABE 2006; Huhnke 2010; Lazarus and Smale 2010; Stinger Ltd. 2010) was used to determine the specific windrower, rake, baler, and stacker to be budgeted. The machinery complement and cost estimator software program MACHSEL (Kletke and Sestak 1991) was used to estimate the fixed and operating costs of the machines based on throughput capacity (tons per hour). The machinery cost equations used in MACHSEL were collected from the American Agricultural Economics Association Costs and Returns Handbook (2000) and the American Society of Agricultural and Biological Engineers (2006).

MACHSEL was updated with current machinery prices for windrower, tractors, rake, baler, and stacker (AGCO Corporation 2010; Stinger Stacker Ltd. 2010) and used to estimate machinery fixed and variable costs. These costs include depreciation, interest on average investment, insurance and taxes, and operating costs including fuel, oil, lubricants, and repairs. Price of harvest machines and machine characteristics, and estimated hours of machinery life are reported in table II-3. Diesel prices (USDA, NASS 2009) and interest rates (Federal Reserve 2009) were updated to 2009 levels.

Biomass harvest and field storage would require machines that could mow, rake, and bale feedstock and require a machine that could collect, transport, and stack bales. Hence, Thorsell's (2004) harvest unit consists of a coordinated set of harvest machines that includes three mowers, three rakes, three balers, nine tractors, a field transporter, and ten laborers. Mapemba (2005) incorporated the harvest unit as designed by Thorsell et al. (2004) in his model which endogenously determined the optimal number of harvest units.

Hwang (2009) recognized that the number of hours suitable for mowing is different from the number of hours suitable for baling and that Mapemba's model very likely overestimated the required number of mowers. Hwang (2009) also recognized that harvest capacity varies across months with the length of day light. Hence, his model was designed to determine independently the optimal number of mowing units and the optimal number of baling units. In this study, the harvest activity is separated into two distinct sets of machines-one for cutting that requires a windrower and another for raking-baling-stacking that requires rakes, balers, and stackers similar to that used by Hwang (2007).

Cutting and Raking-Baling-Stacking Harvest Unit

The budgeted cutting unit consists of a self-propelled windrower (190 Hp) equipped with a 16 foot rotary header (table II-3) and a laborer. Hwang (2007) budgeted mowers with a working throughput capacity of 15.25 tons per hour. The windrower budgeted for this study has a designed working throughput capacity of approximately 38.79 dry tons per hour. The width of the windrower is fixed at 16 feet. The driver of the windrower is assumed to adjust the speed of the windrower to achieve a throughput capacity as near as possible to the working capacity of 38.79 tons per hour. If the stand of switchgrass is very thin (low yielding) the speed of the windrower will be increased. Alternatively, if the stand is very thick (high yielding) the speed will be slower. For a relatively low yield of 2.5 tons per acre, the operating speed is assumed to be 10 miles per hour. However, for a relatively high yield of 6.5 the operating speed is assumed to be about 3 miles per hour. Table II-4 presents the budgeted windrow widths and operating speeds for alternative switchgrass yields for the budgeted windrower.

A raking-baling-stacking harvest unit consists of three wheel rakes, three 55 horsepower tractors; three balers, three 200 horsepower tractors; a field transporter; and seven laborers. Three wheel rakes with working widths of 24 feet powered by 55 Hp tractors with cab; three balers designed to bale 4'x4'x8' rectangular solid bales powered by 200 Hp tractors were selected for budgeting (AGCO Corporation 2010). Thorsell et al. (2004) and Hwang (2007) budgeted a baler with working throughput capacity of 14.78 tons per hour and Sokhansanj, Kumar, and Turhollow (2004) reported a baler capacity of about 15.4 dry tons per hour**.** For this study, a baler which is designed with a throughput working capacity of about 17.21 dry tons per hour was budgeted. For computing cost, the speed of the tractor was assumed to be five miles per hour (Huhnke, 2008). The size of the windrow (dry matter per foot of windrow) is assumed to be adjusted to achieve a throughput capacity as near as possible to the working capacity of 17.21 tons per hour.

The budgeted bale transporter is a Stinger Stacker with spear front end with added squeeze shoot and grapple. The bale transporter coefficients for MACHSEL were based on information provided by Stinger LTD (2010). It is assumed that a stacker would be used to stack bales in the field or at a location within 10 miles of the field. It is also assumed that one Stinger Stacker unit will gather a maximum of eight bales per load and stack them and will have the capacity to gather and stack the bales produced by three balers (Thorsell et al., 2004). Table II-5 presents the budgeted windrow widths and operating speeds for alternative switchgrass yields for rakes, balers, and bale transporters.

Labor

With an extended harvest system, laborers would be on call nine months of the year. It is assumed that salary and benefits cost of each harvest worker for a nine month season is $25,000 (Thorsell et al., 2004). For a two month harvest window system, laborers would be on call for only two months and a labor cost of $5,556 (2/9 * $25,000) is assessed for each harvest worker for the two-month harvest system (table II-6; table II-8).

One laborer is required to operate each windrower. A crew of seven workers would be required to operate the raking-baling-stacking harvest unit that includes three rakes, three balers, and one stacker. The cost of a raking-baling-stacking harvest unit includes labor cost of $175,000 for the nine month harvest system (table II-7) and $38,889 for the two-month harvest system (table II-9).

Harvest Cost

Table II-6 and table II-8 include annual operating and maintenance cost of a cutting unit for several levels of yield for the nine-month and two-month harvest seasons. The annual ownership and the operating cost of a cutting unit for a nine-month harvest season is estimated to be $106,463. This value includes ownership costs (depreciation, interest on average investment, taxes, insurance) and operating costs (fuel, oil, repairs, and lubricants) for a windrower equipped with a rotary header and the cost of labor. If the unit is used for two months per year, the annual ownership and operating cost of the cutting unit is estimated to be $31,263.

The annual ownership and the operating cost of a raking-baling-stacking harvest unit for a nine-month harvest season is estimated to be $545,516. If the unit is only used for two months, the annual ownership and operating cost is estimated to be $169,866. Table II-7 and table II-9 includes estimates of annual operating and maintenance cost of a raking-baling-stacking harvest unit for several yield levels for the nine-month and two-month harvest seasons, respectively.

It is estimated that a single cutting unit (windrower) provides a capacity of 310 tons per eight hour work day. A raking-baling-stacking unit provides an average capacity of 413 tons per eight hour work day. The laborers are expected to work more hours in a day when the weather conditions are favorable, and fewer hours or take a day off when weather conditions are not favorable. Work hours are expected to average 40 hours per week. Since the length of daylight differs across month these daily capacities were adjusted by month (table II-10) using adjustment coefficients reported by Hwang (2007). March was assumed to be a base month. Adjustment coefficients were calculated as the proportion of duration of daylight in each month based relative to March (12 hours). Adjustment coefficients are 0.83 for January, 0.91 for February, 1.00 for March, 1.10 for April, 1.18 for May, 1.21 for June, 1.19 for July, 1.12 for August, 1.03 for September, 0.94 for October, 0.85 for November, and 0.81 for December. For example, daily capacity of a windrower in October is assumed to be 292 tons per day (310 tons per day* 0.94) and daily capacity of a raking-baling-stacking unit in October is 388 tons per day (413 tons per day* 0.94). On the contrary, daily capacity of a windrower in July is assumed to be 369 tons per day (310 tons per day* 1.19) and daily capacity of a raking-baling-stacking unit in October is 492 tons per day (413 tons per day* 1.19).

For safe baling in large rectangular solid bales, it is essential that the moisture content of cut switchgrass material be no more than 15 percent. Therefore, the number of days that switchgrass could be safely baled may be less than the number of days that standing switchgrass may be cut. In addition, harvest days for baling and cutting are different in different counties because harvest operations are heavily weather dependent. The number of harvest days available for cutting and baling in each month for each of the 57 Oklahoma counties included in the model (based on various weather variables and historical weather data) were obtained from Hwang et al. (2007).

Transportation and Storage

The cost to transport harvested biomass from the fields were it is produced to the biorefineries where it is processed is an important component of feedstock cost. Estimates of transportation cost from previous studies vary considerably (Table II-11). Previous studies (Tembo 2000; Mapemba 2005; Hwang 2007) used the biomass transportation cost regression equation reported by Bhat, English, and Ojo (1992). They estimated the cost of transportation for moving biomass from a field to a conversion plant in Tennessee. The transportation cost was estimated based on weekly trucking rates charged by agricultural produce transporters across different U.S. regions. The estimate of total trucking cost for biomass crops such as switchgrass is: total cost per 17 dry ton load = $34.08 + ($1.00 x round trip distance in miles). Based on a round trip distance of 75 miles, the average transportation cost per 17 dry ton load is estimated to be $109.08. The estimated cost per dry ton is $6.42 (table II-11).

Petrolia (2008) estimated biomass transportation cost for delivering corn-stover biomass from biomass supplying counties to plant locations in Minnesota. He assumed that 27 square bales can be loaded for a total weight of 22.37 tons per truck. He reported a cost per loaded mile of $1.75, $1.38, and $1.23 for loads for travelling within 25 miles, between 25 and 100, and for travelling more than 100 miles, respectively. Based on his reported transportation cost, it is estimated that this system would cost $117.36 per load or $5.25 per ton for a round trip distance of 75 miles. Hess et al. (2009) assumed that 26 rectangular solid bales (4' x 4' x 8') can be loaded per truck for a total weight of 18.9 tons. Based on their reported transportation cost, it is estimated that this system would cost $228.63 per load or $12.10 per ton for a round trip distance of 75 miles.

Brechbill and Tyner (2008) estimated cost of transporting switchgrass biomass from supplying locations to an Indiana biorefinery. They estimated total trucking cost per 13 dry ton load = $14.95 + ($1.81 x round trip distance in miles). Based on a round trip distance of 75 miles, the average transportation cost per 13 dry ton load is estimated to be $150.70. The estimated cost per dry ton is $11.59. Kumar et al. (2004) estimated the cost of transporting straw by truck. By using a similar equation, Sokhansanj et al. (2009) estimated the cost of transporting switchgrass biomass. For a round trip distance of 75 miles, the average transportation cost of a 20 dry ton load was estimated to be $253.40, or $12.67 per dry ton.

For the present study, a transportation cost equation is estimated from data provided by Wang (2009). Transportation costs depend on the distance the feedstock will be shipped from the fields to the biorefinery. The distance between any biomass supplying county and any plant location is estimated by the distance from the county's central point to the plant location. Wang (2009) estimated the costs to transport switchgrass from fields in Tennessee to a biorefinery located in Tennessee. Wang (2009) assumed that a semi-tractor trailer could transport 16 dry tons of rectangular solid bales per load. The equation used to calculate biomass transportation costs for a 16 dry ton truck load is:

(1) $$TRC_{ij} = 12.78 + 1.72d_{ij}$$

where TRC_{ij} is the estimated transportation cost in dollars per 16 dry ton truck load for transporting biomass from the supplying county *i* to the biorefinery plant location j; d_{ij} is the round-trip distance in miles. Feedstock transportation costs per ton are calculated by dividing TRC_{ij} by the truck capacity of 16 dry tons. Based on a round trip distance of 75 miles, the average transportation cost per load is estimated to be \$141.78. The estimated cost per dry ton is \$8.86.

Storage losses at the biorefinery and in the field are assumed to be one percent per month (Hwang 2007, p 72). Another assumption is that bales stored in the field would be covered with a plastic tarp. The cost of field storage is estimated to be \$2 per ton regardless of the number of months the material is in storage (Tembo 2000, p 59; Hwang, 2007, p 72).

Model

A multi-region, multi-period, mixed integer mathematical programming model originally described by Tembo, Epplin and Huhnke (2003) and used and modified by Mapemba et al. (2007) and Hwang (2007) is extended, modified, and enhanced to determine the cost to deliver a ton of switchgrass biomass to a 2000 tons per day biorefinery. A full description of the model is presented in chapter III. Descriptions of all indices, parameters and variables used in the model are summarized in the list of symbols at the beginning of this dissertation. This model is designed and solved to answer a number of very specific questions about the economics of a lignocellulosic biomass biorefinery. It is assumed that land leasing, feedstock production, harvest, storage, and transportation will be centrally managed by the biorefinery.

The objective function is to maximize the net present value of a biomass biorefinery industry subject to a set of constraints (Chapter III). The model simultaneously determines optimal decisions for all levels from switchgrass harvest through ethanol processing for all months. The model simultaneously determines the optimal location; the area and quantity of switchgrass harvested by county, by month, and by land category; the optimal number of harvest machines; to produce, harvest, store, and transport a flow of switchgrass biomass to the biorefinery. The model is solved for both an extended harvest window (July through March) and for a restricted harvest window (September and October).

Constraints (Chapter III) are set so that the model will optimally choose one 2000 tons per day biorefinery location from among six potential biorefinery sites. The biorefinery locations are included in the model as binary variables. The model determines the number of acres in each county (from among 57 counties) and the type of land (either cropland or improved pasture land) for switchgrass production. In this study, arbitrarily switchgrass production is restricted to occupy no more than ten percent of the cropland of a county and no more than ten percent of the improved pasture land of a county. The model determines how many acres from which county and which land class are optimal to harvest for each month; how much harvested biomass should be put in field storage each month; how much should be shipped to the biorefinery each month; how much should be put in biorefinery storage each month; and how much should be processed each month. The model accounts for differences in nitrogen and phosphorus fertilizer requirements depending on month of harvest. An integer variable is included to determine the optimal number of mowing units (windrowers) and another integer variable to determine the optimal number of harvest units (rakes, balers, tractors, and stackers). The model accounts for storage losses as a function of months stored.

Six different systems are modeled to capture the differences in cost per ton of delivered switchgrass feedstock. In four models (model 1 though 4), the harvest season is permitted to extend from July through March (nine-month (9m) system). In two models (model 5 and 6), the harvest season is restricted to September and October (two-month (2m) system). Model 1 accounts for differences in expected yield (Ym) and nitrogen requirements (Nm) depending on month of harvest and permits switchgrass establishment on both cropland (Crop) and improved pasture land (Past) (9mYmNmCropPast); Model 2 restricts land used to only cropland (9mYmNmCrop); Model 3 assumes a fixed level of nitrogen fertilizer of 80 pounds per acre per year independent of harvest month (9mYmN80CropPast); Model 4 assumes switchgrass yields would be the same independent of harvest month (9mYmaxNmCropPast). Model 5 uses the assumptions of Model 1 regarding expected yield and nitrogen requirements, but limits harvest to September and October (2mYmNmCropPast). Model 6 uses the assumptions of Model 2, but limits harvest to September and October (2mYmNmCrop).

Results

Table II-12 includes a summary of the results of estimated costs, number of harvest units, harvested acres, and tons harvested to provide a flow of switchgrass feedstock to a biorefinery for each of the six models that maximizes net present value.

Comparison of Results of Model 1 (9mYmNmCropPast) with Model 5(2mYmNmCropPast)

Restricting harvest to two months (Model 5) increases the costs of delivering feedstock by about $12 per ton over the costs for the nine-month harvest system. The estimated costs for land rent, establishment, maintenance, harvest, storage, and transportation for the nine-month harvest window is $52 per ton versus $64 for the two-month window (Table II-12, Figure II-3). Most of this cost difference can be attributed to the difference in harvest costs which are estimated to be $15 per ton more for the two-month harvest system. The two-month harvest system requires substantially more harvest machines which increases the machinery ownership costs per ton. The optimal number of harvest units for cutting increases from 18 for the nine-month harvest window to 96 for the two-month harvest window, and the optimal number of raking-baling-stacking harvest units increases from 14 for the nine-month harvest window to 100 for the two-month harvest window. The increase in harvest machines is not proportional since the months do not contain the same number of harvest days and the number of hours available for harvest differs across month. Based on historical weather data, in most years, October is expected to have relatively few days during which switchgrass may be safely baled (Hwang et al., 2009).

The 2,000 tons per day biorefinery requires 700,000 tons per year (assuming 350 days of operation per year). The total biomass harvested for the nine-month and two-month systems is 710,649 and 737,918 tons, respectively (Table II-12). More biomass is harvested for the two-month season to compensate for the additional storage losses, which are modeled as a function of the time in storage. Hence, the harvested tons requirement is greater for the two-month harvest system than for the nine-month harvest system. For a nine-month harvest system, only 71,400 tons and 32,592 tons are scheduled for harvest in September and October, respectively. But when the harvest window is restricted to September and October, 509,166 and 228,752 tons are scheduled for harvest in September and October, respectively. The chart in Figure II-4 illustrates the number of tons harvested per month for both systems.

Figure II-5 illustrates total harvested acres of cropland and improved pasture land for both the nine-month and two-month harvest systems (Model 1 and 5). As noted in Table II-2, one disadvantage of an extended harvest season is that harvestable yield per acre declines if harvest is extended beyond October. As a result, fewer acres are required for the two-month harvest system (122,577) than for the nine-month harvest system (144,208). The model enables a holistic comparison of the economic tradeoffs between the increased harvestable yield per acre from the two-month harvest system versus the rather substantial decrease in harvest costs per ton for the nine-month system. Leasing an additional 21,600 acres and establishing switchgrass on it is more economical than investing in and maintaining an additional 78 windrowers and 86 raking-baling-stacking harvest units (258 more rakes, 258 more 55 Hp tractors, 258 more balers, 258 more 200 Hp tractors, 86 more stackers). Details of the economic tradeoffs are provided in Table II-

12. The nine-month harvest season optimally requires more acres, which results in greater land rent, establishment and maintenance costs, and fertilizer cost per ton of delivered switchgrass. However, these costs are substantially less than the additional harvest and storage costs of the two-month harvest system.

Comparison of Results of Model 1 with Model 2, 3, and 4 and Model 5 with Model 6

As noted for Model 1, land available for switchgrass production for each county is restricted to no more than ten percent of the total cropland and no more than ten percent of the total improved pasture land. Even though the county yield is assumed to be the same for both land types, and the lease rate is assumed to be $20 per acre more for cropland, Model 1 optimally selects a combination of cropland and improved pasture land. Leasing more costly cropland close to a biorefinery is more economical than leasing less costly land at a greater distance, transporting the feedstock, and incurring the additional transportation cost.

Model 2 differs from Model 1 in that switchgrass production is limited to cropland. As reported in Table II-12 a major finding is that if production is not permitted on improved pasture land, the optimal plant location shifts from Pontotoc to Canadian County. The region including Canadian and surrounding counties has a higher percentage of cropland relative to total land. The optimal plant location differs as a result of the interactions between transportation cost and available land area, and the estimated total cost of delivered feedstock increases from $52 to $59 per ton when the model is not permitted to lease improved pasture land. As reported in Table II-12 more acres are required for Model 2 because the expected switchgrass yield is lower in the Canadian County region than in the Pontotoc County region (figure II-1). Hence, restricting switchgrass production only to cropland results in greater land rent, nitrogen costs, phosphorus costs, and transportation costs per ton of delivered switchgrass.

Models 5 and 6 enable a similar comparison of limiting production to cropland versus both cropland and improved pasture land for a two-month harvest window. Production is limited to no more than ten percent of a county's cropland acres for Model 6. In this case, the optimal plant location shifts from Pontotoc to Garfield County (Table II-12). The cost to deliver feedstock increases from $64 to $67 per ton with the reduction in access to improved pasture land. When the harvest window is reduced from nine to two months, the restriction to use only cropland is not as costly. When the plant location is moved from Pontotoc to Garfield County, switchgrass production moves to a region with substantially more September and October harvest days, which requires a smaller investment in harvest machines.

In Model 3, the variable nitrogen rate by harvest month assumption (Model 1) is replaced with an assumption that 80 pounds per acre per year of actual nitrogen would be applied to the established stands of switchgrass for all harvest months. (Eighty pounds per acre would be required to achieve the plateau yield if the biomass is harvested in July). This change increases the estimated cost of nitrogen by $1.20 per ton of switchgrass delivered, but results in few other changes. Figure II-6 illustrates nitrogen fertilizer required (pounds) on total harvested acres from Model 1 and Model 3.

For Model 4, switchgrass yield is assumed to be at the highest level independent of the harvest month relative to Model 1, in which the harvestable yield is a function of harvest months as reflected in Table II-2. Assuming the same yield per month reduces the estimated cost to deliver a ton of feedstock by $4.58 per ton.

Summary and Conclusion

Year-round operation of a cellulosic biorefinery will require year-round delivery of feedstock. In Oklahoma switchgrass cannot be harvested in every month. Harvesting switchgrass during a relatively narrow window (September and October) may result in the largest harvestable yield per acre and minimal requirements for nitrogen fertilizer, but would require a relatively large investment in harvest machines and a large investment in storage. Extending switchgrass harvest over many months (July through March) would require a smaller investment in harvest machines, but would result in a lower average harvestable yield per acre and would require more nitrogen fertilizer. To address this issue a model is constructed to: (i) determine the cost to deliver a ton of switchgrass biomass from cropland and improved pasture land to a biorefinery, optimally located in Oklahoma, which can process 2,000 dry tons per day; (ii) compare the results from a model that permits a harvest window from July through March with the results from a model that restricts harvest to September and October while model accounts for differences in yield and nitrogen fertilizer requirements across harvest months; (iii) update the set of machines budgeted and update estimates of machinery costs for harvesting switchgrass (Thorsell et al., 2004; Hwang, 2007).

Based on the assumptions included in the model that consider many of the tradeoffs encountered when the length of the harvest window is changed, the strategy of extending harvest over many months is economically preferable to a strategy of harvesting only in peak yield harvest months. Results confirm that, as expected, nitrogen and land requirements are greater, but harvest machinery investment requirements are lower for an extended harvest season strategy (nine-month harvest season) than restricted harvest window (two-month harvest season). Based on the model results, a two-month harvest season would increase the cost to deliver feedstock by 23 percent.

The estimated cost to deliver a flow of feedstock to a 2,000 dry tons per day biorefinery is reduced from $64 per ton for a two-month harvest season to $52 per ton for a nine month harvest season mainly because of the reduction in the number of required harvest machines and the reduction in the cost of storage. A wide harvest window would enable the use of harvest machinery and harvest crews during nine months. So, the fixed costs of harvest machines can be spread across many more acres which reduces the fixed costs of harvest machinery per ton of feedstock, and also reduces the required investment in harvest machines. This finding illustrates that while estimating the cost of delivered feedstock to a biorefinery, harvest window matters and also suggests that a wide harvest window would be economically preferable to a narrow harvest window.

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APPENDIX FOR CHAPTER II

Table II-1: Estimated Cost of Delivering Switchgrass Biomass to a Biorefinery Reported by Selected Prior Studies

		Cost $/dry ton					
Source	Location	Land Cost	Production Cost	Harvest Cost	Storage Cost	Transportation Cost	Total Cost
Epplin (1996)	Oklahoma	7.46	4.67	10.80		10.70	33.66
Duffy (2007)	Iowa	20	29.9	32.33	16.67	14.75	113.66
Epplin et al. (2007)	Oklahoma	10.77	9.23	16.30	0.58	12.00	48.88
Khanna, Dhungana, and Brown (2008)	Illinois	30.25	12.97	34.87	3.75	7.17	89.01
Mooney et al. (2008)	Tennessee	15.74	12.93	24.32			53.03
Sokhansanj et al. (2009)	USA		37.64	21.51		13.99	73.14

Table II-2. Switchgrass Yield and Nitrogen Differences by Month

Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Proportion of Potential Switchgrass Yield by Harvest Month											
0.80	0.75	0.70	0	0	0	0.79	0.86	1.00	1.00	0.90	0.85
Level of Nitrogen (pounds per acre) by Harvest Month											
63	63	63	0	0	0	80	74	69	63	63	63

Table II-3. Prices of Harvest Machines and Expected Hours of Machine Life

Unit	List Price ($)	Hours of Life*
Self Propelled Windrower MF 9635	93,613	3,000
16 feet Rotary header MF 9190	40,982	3,000
55 Hp MFD Tractor with cab MF 3625	44,383	12,000
24 feet Wheel rake MF 3986	17,285	2,500
Large Square Baler (4x4x8) MF 2190	156,140	3,000
200 Hp MFD Tractor MF DT205B	203,787	16,000
Bale Transporter Stacker	186,000	10,000

Note: A self-propelled windrower equipped with a 16 foot rotary header.
A rake is pulled by a 55 horsepower tractor.
A baler is pulled by 200 horsepower tractor.
Self-propelled bale transporter collects as many as eight large rectangular solid bales, transports them and stacks them in the field or at a location within ten miles.
Source: AGCO Corporation (2010) and Stinger Ltd. (2009).
*Source: Agricultural Machinery Management Data (2009). American Society of Agricultural and Biological Engineers.

Table II-4. Budgeted Operating Speeds for Alternative Switchgrass Yields and Windrow Widths for Windrowers

Yield (tons/acre)	Windrow Width (feet)	Efficiency (%)	Speed (miles/hour)
2.0	16	0.80	12.50
3.0	16	0.80	8.33
4.0	16	0.80	6.25
5.0	16	0.80	5.00
6.0	16	0.80	4.17

Table II-5. Budgeted Operating Field Efficiency, Speeds for Alternative Switchgrass Yields and Windrow Widths for Rakes, Balers, and Bale Transporter Stacker

	Windrow Width (feet)			Speed (miles/hour)		
Yield (tons/acre)	Rake	Baler and Bale Transporter Stacker	Efficiency (%)	Rake	Baler	Bale Transporter Stacker
1.0	24	35.50	0.80	7.39	5	15
2.0	24	17.75	0.80	3.70	5	15
3.0	24	11.83	0.80	2.46	5	15
4.0	24	8.88	0.80	1.85	5	15
5.0	24	7.10	0.80	1.48	5	15
6.0	24	5.92	0.80	1.23	5	15

Table II-6. Annual Operating and Maintenance Cost of a Cutting Unit (Self-Propelled Windrower (190 Hp) Equipped with a 16 Foot Rotary Header) for a Nine-Month Harvest Window

	Yield per Acre (Tons)						
	1	2	3	4	5	6	Average
Total Annual Acres	44,684	22,342	14,895	11,171	8,937	7,447	
Total Labor Cost	25,000	25,000	25,000	25,000	25,000	25,000	
Total Fixed Costs	22,969	22,969	22,973	22,969	22,969	22,959	
Variable Machinery Costs excluding Fuel Cost	31,273	31,273	31,286	31,273	31,273	31,246	
Fuel Cost	27,226	27,226	27,238	27,226	27,227	27,203	
Total Variable Machinery Costs	58,499	58,499	58,524	58,499	58,500	58,449	
Total Annual Costs	106,468	106,467	106,497	106,468	106,469	106,408	106,463
Total Per Acre Costs ($)	2.38	4.77	7.15	9.53	11.91	14.29	
Total Per Ton Costs ($)	2.38	2.38	2.38	2.38	2.38	2.38	

Note: A cutting unit includes one laborer and one self propelled windrower with a 16' rotary cutoff head.
Interest rate used in MACHSEL is 8%.
Price of diesel used in MACHSEL is $2.57 per gallon.

Table II-7. Annual Operating and Maintenance Cost of a Raking- Baling-Stacking Harvest Unit for Nine-Month Harvest Window

	Yield per Acre (Tons)						
	1	2	3	4	5	6	Average
Total Annual Acres	48,057	24,029	16,019	12,014	9,611	8,010	
Total Labor Cost ($/HU)	175,000	175,000	175,000	175,000	175,000	175,000	
	Raking						
Total Fixed Costs ($/HU)	15,755	15,744	15,765	15,744	15,743	15,766	
Variable Costs excluding Fuel Cost ($/HU)	24,262	24,230	24,295	24,229	24,229	24,297	
Fuel Cost ($/HU)	19,117	19,091	19,143	19,090	19,090	19,144	
Total Variable Machinery Costs ($/HU)	43,379	43,321	43,438	43,320	43,319	43,441	
	Baling						
Total Fixed Costs ($/HU)	86,454	86,455	86,468	86,454	86,466	86,430	
Variable Machinery Costs excluding Fuel Cost ($/HU)	134,167	134,170	134,220	134,164	134,214	134,069	
Fuel Cost ($/harvest unit)	69,452	69,453	69,479	69,450	69,476	69,401	
Total Variable Machinery Costs ($/HU)	203,618	203,623	203,699	203,614	203,690	203,470	
	Field Transporter-Stacker						
Total Fixed Costs ($/HU)	16,888	16,879	16,873	16,867	16,862	16,857	
Variable Machinery Costs excluding Fuel Cost ($/HU)	198	541	1,030	1,664	2,445	3,365	
Fuel Cost ($/HU)	831	1,663	2,495	3,325	4,158	4,984	
Total Variable Machinery Costs ($/HU)	1,029	2,203	3,525	4,989	6,604	8,348	
Total Annual Costs ($/HU)	542,123	543,226	544,767	545,987	547,684	549,313	545,516
Total Per Acre Costs ($)	12	24	37	49	61	74	
Total Per Ton Costs ($)	12	12	12	12	12	12	

A raking-baling-stacking harvest unit consists of three wheel rakes, three 55 horsepower tractors; three balers, three 200 horsepower tractors; a bale transporter stacker; and seven laborers.

Table II-8. Annual Operating and Maintenance Cost of a Cutting Unit for Two-Month Harvest Window

	Yield per Acre (Tons)						
	1	2	3	4	5	6	Average
Total Annual Acres	9930	4965	3310	2482	1986	1655	
Total Labor Cost ($)	5556	5556	5556	5556	5556	5556	
Total Fixed Costs ($)	13,513	13,513	13,514	13,514	13,513	13,511	
Variable Machinery Costs excluding Fuel Cost ($)	6,144	6,144	6,146	6,146	6,144	6,138	
Fuel Cost ($)	6,050	6,050	6,053	6,053	6,050	6,046	
Total Variable Machinery Costs ($)	12,194	12,194	12,199	12,199	12,194	12,183	
Total Annual Costs ($)	31,263	31,263	31,269	31,269	31,263	31,250	31,263
Total Per Acre Costs ($)	3.15	6.30	9.45	12.60	15.74	18.88	
Total Per Ton Costs ($)	3.15	3.15	3.15	3.15	3.15	3.15	

Note: A cutting harvest unit includes one labor, one Self Propelled Windrower with a 16' rotary cutoff head.
Interest rate used in MACHSEL is 8%.
Price of Diesel used in MACHSEL is $2.57 per gallon.

Table II-9. Annual Operating and Maintenance Cost of a Raking-Baling-Stacking Harvest Unit for Two-Month Harvest Window

	Yield per Acre (Tons)						
	1	2	3	4	5	6	Average
Total Annual Acres	10679	5340	3560	2670	2136	1780	
Total Labor Cost ($/HU)	38889	38889	38889	38889	38889	38889	
Raking Harvest Unit							
Total Fixed Costs ($/HU)	7,842	7,838	7,847	7,838	7,838	7,847	
Variable Costs excluding Fuel Cost ($/HU)	5,391	5,385	5,399	5,385	5,385	5,399	
Fuel Cost ($/HU)	4,248	4,243	4,254	4,243	4,243	4,254	
Total Variable Machinery Costs ($/HU)	9,640	9,627	9,653	9,627	9,627	9,653	
Baling Harvest Unit							
Total Fixed Costs ($/HU)	46,925	46,927	46,934	46,927	46,934	46,912	
Variable Machinery Costs excluding Fuel Cost ($/HU)	29,814	29,817	29,828	29,817	29,828	29,793	
Fuel Cost ($/harvest unit)	15,433	15,435	15,441	15,434	15,441	15,422	
Total Variable Machinery Costs ($/HU)	45,247	45,251	45,269	45,251	45,269	45,216	
Field Transporter-Stacker							
Total Fixed Costs ($/HU)	16,888	16,879	16,873	16,867	16,862	16,857	
Variable Machinery Costs excluding Fuel Cost ($/HU)	198	541	1,030	1,664	2,445	3,365	
Fuel Cost ($/HU)	831	1,663	2,495	3,325	4,158	4,984	
Total Variable Machinery Costs ($/HU)	1,029	2,203	3,525	4,989	6,604	8,348	
Total Annual Costs ($/HU)	166,459	167,614	168,990	170,387	172,022	173,722	169,866
Total Per Acre Costs ($)	17	34	51	69	87	105	
Total Per Ton Costs ($)	17	17	17	17	17	17	

Table II-10. Harvest Capacity for Cutting Unit and Raking-Baling-Stacking Unit for Each Month Adjusted by the Length of Daylight (tons/day)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cutting	258	282	310	341	366	375	369	348	320	292	264	251
Raking-Baling-Stacking	343	376	413	454	487	500	492	463	425	388	351	335

Table II-11. Biomass Transportation Cost Estimates

Source	Location	Truck Size (dry ton)*	Transportation cost equation	Cost per ton Round Trip Distance from Field to Biorefinery (miles)		
				50	75	150
Bhat et al. (1992)	Tennessee	17	$TRC_{ij} = 34.08 + 1.00d_{ij}$	4.95	6.42	10.83
Petrolia (2008)	Minnesota	22.37	$TRC_{ij} = 36.36 + 1.08d_{ij}$	4.04	5.25	8.87
Brechbill and Tyner (2008)	Indiana	13	$TRC_{ij} = 14.95 + 1.81d_{ij}$	8.11	11.59	22.03
Wang (2009)	Tennessee	16.01	$TRC_{ij} = 12.78 + 1.72d_{ij}$	6.17	8.86	16.91
Kumar, Cameron, and Flynn (2004) and Sokhansanj et al. (2009)	Canada/USA	20	$TRC_{ij} = 103.4 + 2.00d_{ij}$	10.17	12.67	20.17
Hess et al. (2009)	USA	18.9	$TRC_{ij} = 14.13 + 2.86d_{ij}$	8.31	12.10	23.45

Note: TRC_{ij} is the estimated transportation costs in dollars per dry ton truck load for transporting biomass from location i to location j and d_{ij} is the round-trip distance in miles. The round trip distance is assumed to be twice the distance from the field to the biorefinery.
*Truck capacities (dry ton) are reported based on respective studies.

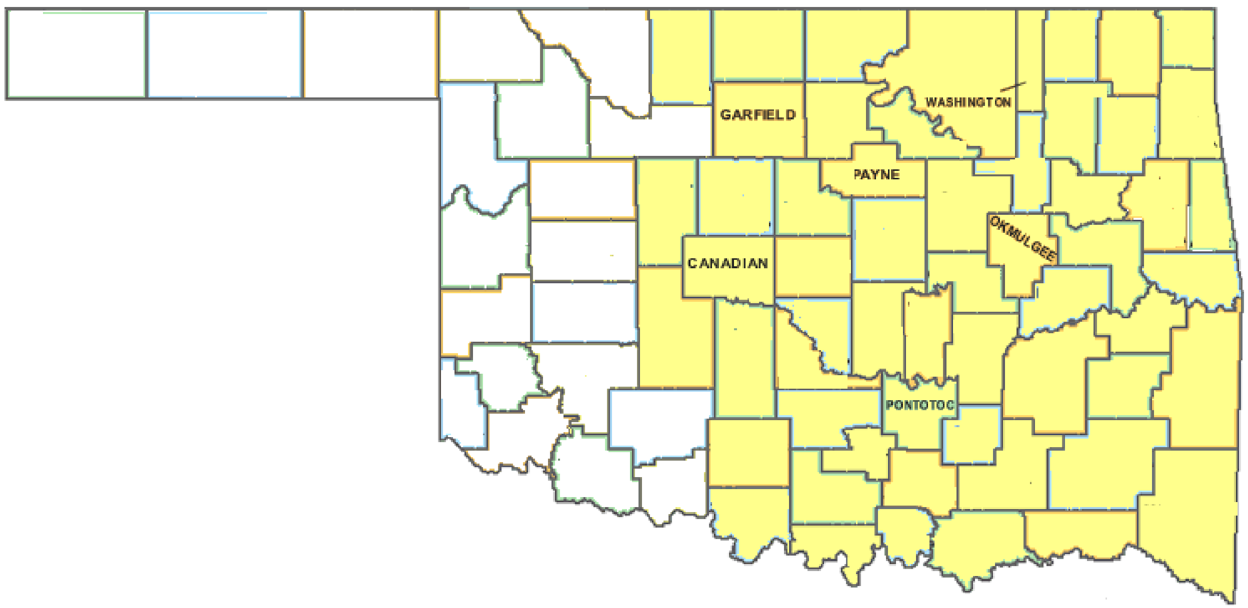
Table II-12. Comparison of Results of Five Models for Estimated Costs, Number of Harvest Units, Harvested Acres, and Tons Harvested to Provide a Flow of Switchgrass Feedstock to a 2,000 Dry Tons per Day Biorefinery

	Model Comparison Nine-month harvest window				Two-month harvest window	
Category	Model 1 (Cropland & Improved Pasture)	Model 2 (Only Cropland)	Model 3 (Nitrogen level fixed at 80 lb/ac for all harvest months)	Model 4(Yield fixed at highest level for all harvest months)	Model 5 (Cropland & Improved Pasture)	Model 6 (Only Cropland)
Plant location (county)	Pontotoc	Canadian	Pontotoc	Pontotoc	Pontotoc	Garfield
Land rent ($/ton)	9.29	13.99	9.29	7.79	7.97	12.63
Establishment & maintenance cost ($/ton)	6.16	7.46	6.16	5.09	5.24	6.74
Cost of Nitrogen ($/ton)	6.38	7.24	7.58	5.26	5.42	6.49
Cost of Phosphorus ($/ton)	0.39	0.45	0.40	0.34		
Total field cost ($/ton)	12.92	15.15	14.13	10.69	10.66	13.22
Harvest cost ($/ton)	13.65	13.50	13.65	13.65	28.55	25.61
Field storage cost ($/ton)	0.41	0.41	0.41	0.41	1.66	1.65
Transportation cost ($/ton)	16.02	16.33	16.02	15.17	15.47	14.08
Total cost of delivered feedstock ($ /ton)	52.29	59.37	53.50	47.71	64.30	67.20
Harvest units for cutting (no.)	18	17	18	18	96	79
Harvest units for baling (no.)	14	14	14	14	100	91
Biomass harvested from cropland (tons)	197,795	710,650	191,287	217,297	208,820	737,732
Biomass harvested from improved pasture land (tons)	512,853		519,362	493,302	529,098	
Total Biomass Harvested (dry tons)	710,649	710,650	710,649	710,599	737,918	737,732
Cropland harvested (acres)	36,592	163,202	36,592	34,976	33,672	147,359
Improved pasture land harvested (acres)	107,616		107,616	83,887	88,905	
Total land harvested (acres)	144,208	163,202	144,208	118,864	122,577	147,359

Source: Digital-topo-maps (2005).

Switchgrass yield were collected from Graham, Allison, and Becker (1996) and experts opinion (Tembo, 2000).

Figure II-1. Map showing switchgrass yield (tons/acre) estimates at the peak harvest month by county.



Source: Degital-topo-maps (2005).

Figure II-2. Map showing potential six biorefinery locations in Oklahoma. Each of Oklahoma's 57 (in yellow) counties designated as a potential switchgrass production regions.

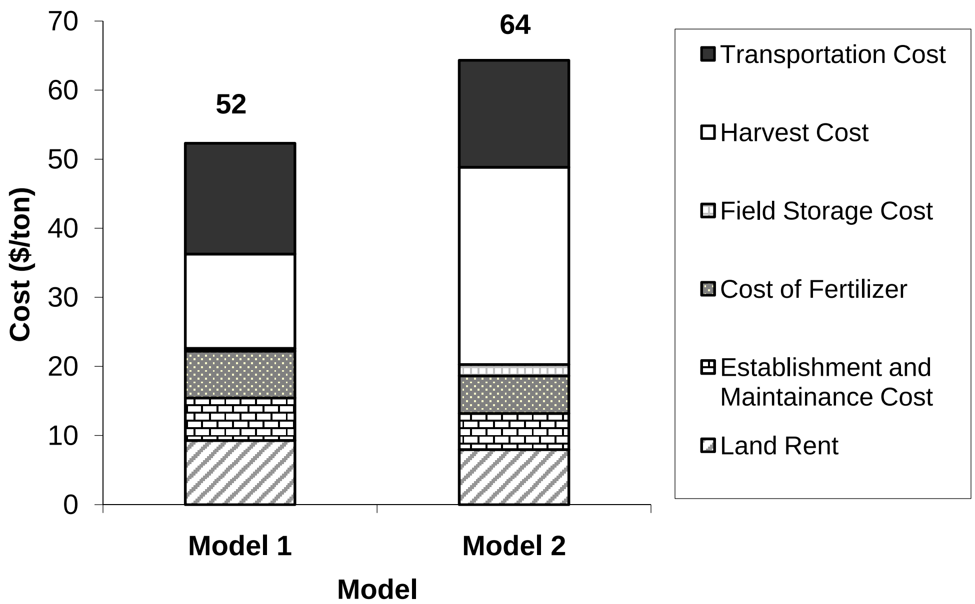


Figure II-3. Estimated costs ($/ton) to provide a flow of switchgrass feedstock to a 2,000 dry tons per day biorefinery for both nine-month (model 1) and two-month (model 5) harvest window.

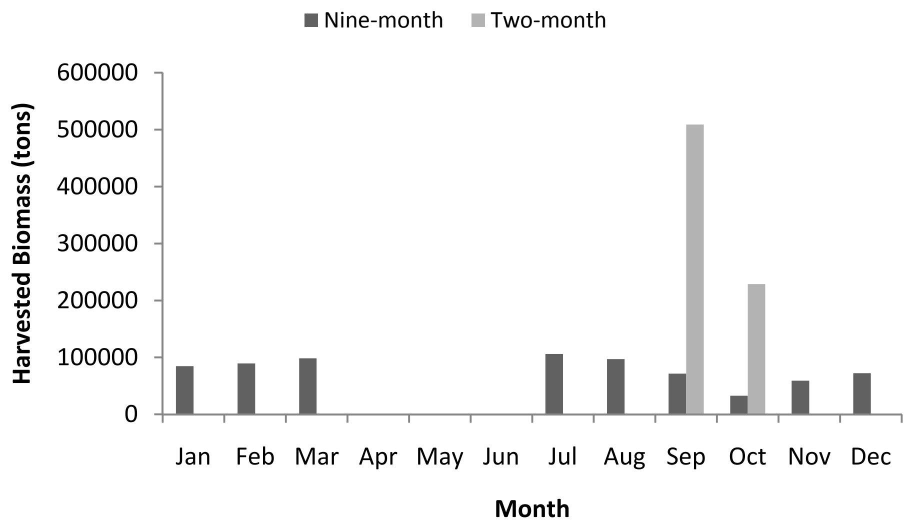


Figure II-4. Switchgrass harvested per month for nine-month and two-month harvest system to provide a flow of feedstock to a 2,000 dry tons per day biorefinery with variable yield and variable nitrogen requirements by harvest month considering both cropland and improved pasture (results from Models 1 (9mYmNmCropPast) and 5 (2mYmNmCropPast)).

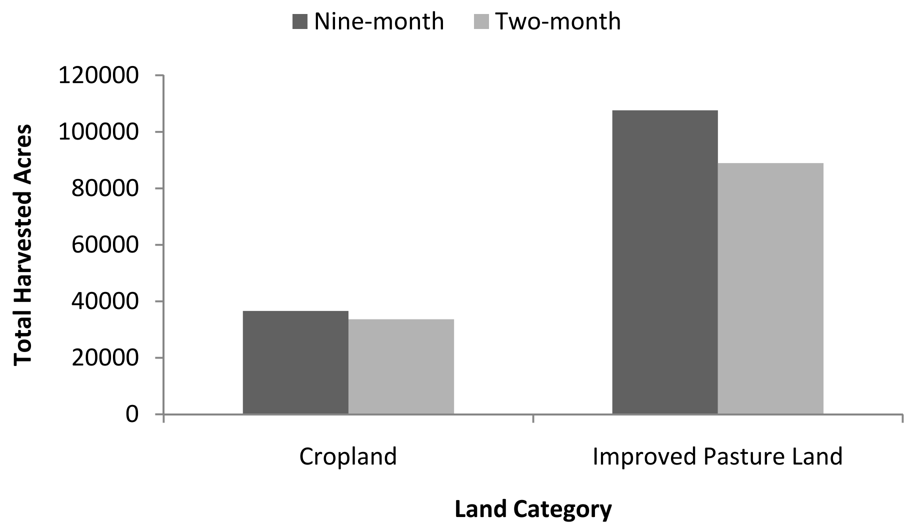


Figure II-5. Total harvested acres of cropland and improved pasture land for nine-month and two-month harvest system (results from Models 1 (9mYmNmCropPast) and Model 5 (2mYmNmCropPast)).

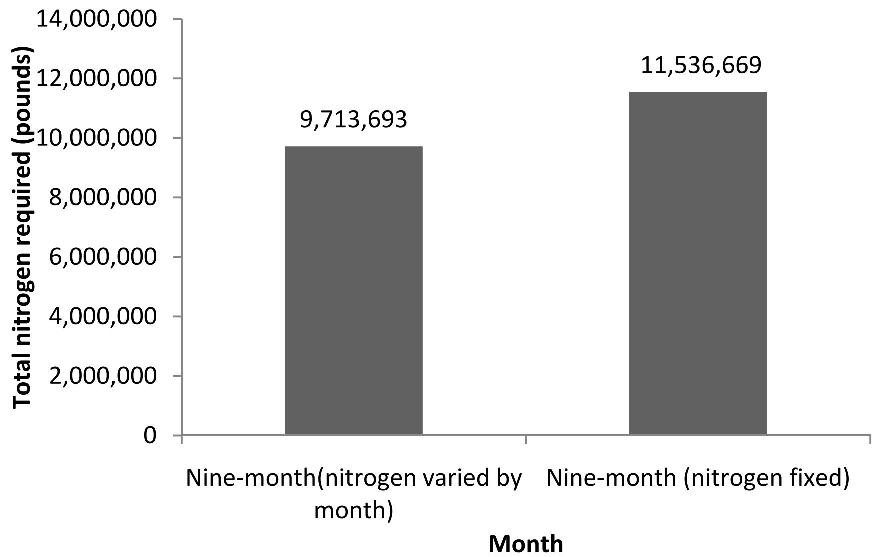


Figure II-6. Nitrogen fertilizer required (pounds) on total harvested acres for both nine-month when nitrogen requirement is varied by month of harvest (results from Models 1 (9mYmNmCropPast) and for nine-month harvest system when nitrogen is fixed independent of harvest month (Model 3, 9mYmN80CropPast).

CHAPTER III

SWITCHGRASS TO ETHANOL: A FIELD TO FUEL APPROACH

Abstract

The U.S. Energy Independence and Security Act of 2007 mandates the production of 16 billion gallons of cellulosic biofuels by 2022. Previous studies have identified several technical categories for producing ethanol from cellulose. Desirable feedstock properties, biomass to biofuel conversion rate, and investment required in plant and equipment differs depending on which of several competing technologies is used. But no commercial sized facilities were operating in 2009 suggesting that development of a commercially viable system for production of cellulosic ethanol has not progressed as rapidly as anticipated. The objective is to determine the breakeven ethanol price for a cellulosic biorefinery. A comprehensive mathematical programming model that encompasses the chain from land acquisition to ethanol production is constructed and solved. Given the uncertainty regarding biorefinery capital requirements and the biomass to biofuel conversion rate, the breakeven ethanol price is computed for 12 different combinations of investment cost and conversion rates. For a base model with a capital requirement of $400 million for a 100 million gallons per year biorefinery and a conversion rate of 100 gallons of ethanol per dry ton, the breakeven ethanol price is $1.93 per gallon: $0.22 per gallon for land rental, switchgrass production, and field storage;

$0.14 per gallon for feedstock harvest; $0.18 per gallon for feedstock transportation; $0.75 per gallon for biorefinery operation and maintenance; and $0.64 per gallon for biorefinery investment. Biomass to ethanol conversion rate and the cost of biorefinery construction, operation, and maintenance are critical issues in the cost of producing ethanol from lignocellulosic feedstocks.

Introduction

In a frequently referenced *Science* article, Lynd et al. (1991) hypothesized that given continued investment in research, by the year 2000, technology would be developed enabling the production of cellulosic ethanol for a wholesale selling price of $0.60 per gallon ($1.19 in 2009 dollars). In 2006, Pacheco reported to a U.S. Senate committee that "…Our goal is to reduce the cost of producing cellulosic ethanol from $2.25 a gallon in 2005, to $1.07 in 2012. …" In addition, the U.S. Department of Energy (2010) projected cellulosic conversion costs (the cost of producing cellulosic ethanol, exclusive of feedstock costs) of $0.92 per gallon and feedstock costs (including cost of harvesting, storage, preprocessing and transportation) of $0.39 per gallon by 2012.

In anticipation of an economically viable feedstock production and conversion system, the U.S. Energy Independence and Security Act (EISA) of 2007 included a provision that by 2022, 16 billion gallons of cellulosic biofuels, primarily cellulosic ethanol, be produced and blended with gasoline. Since, no unsubsidized commercial sized facilities were operating in 2009, it seems reasonable to conclude that development of a commercially viable system for production of cellulosic ethanol has not progressed as rapidly as anticipated.

The United States Environmental Protection Agency (USEPA) has responsibility for implementing the provisions of EISA. They have identified six methods or technical categories for producing ethanol from cellulose (biochemical enzymatic hydrolysis; thermochemical/catalytic; thermochemical/biochemical; strong acid hydrolysis; dilute acid, steam explosion; consolidated hydrolysis and fermentation) (USEPA 2010, p. 115). These methods have several important differences that influence field to fuel economics. The (a) desirable feedstock properties, (b) biomass to ethanol conversion rate and (c) investment required in plant and equipment differs across systems.

For year round operation, all of these systems would require a flow of feedstock throughout the year. Enzymatic hydrolysis requires specific enzymes to convert a given type of feedstock and a homogeneous mixture of feedstock would be preferable (Wei, Pordesimo, and Batchelor 2007). Gasification can handle a wider variety of feedstock. Net feedstock costs could be expected to be greater for conversion systems that have narrower tolerances on biomass characteristics. Characteristics that define feedstock quality remain to be determined.

There is considerable variability in expected conversion rates (table III-1). For example, the USEPA (2010) reports conversion rates of 72 gallons per dry ton (p. 721), 90 gallons per dry ton (p. 285), and 94 gallons per dry ton (p. 286), depending on system and maturity of the system. Schmer et al. (2008) used 91 gallons per dry ton. Coskata (2010) reports on their web site that their semi-commercial facility produces 100 gallons of ethanol per dry ton. The U.S. Department of Energy (2010) has projected a conversion rate of 89.9 gallon per dry ton by 2012. For a given size biorefinery, total feedstock requirements, acres required and transportation distances from feedstock production region to biorefinery would differ greatly between a plant that achieved 100 versus one that produced only 70 gallons per dry ton.

Capital costs required to construct a commercial-scale biorefinery depends on the conversion technology. The USEPA (2010) reported estimates of expected capital costs computed by the Department of Energy's National Renewable Energy Laboratory (NREL). NREL estimated expected capital cost of $232 million for a biochemical conversion plant with an annual capacity 56 million gallons (USPEA 2010, p. 751). For a thermochemical plant designed to produce an ethanol yield of 63 million gallons per year NREL estimates an expected capital cost of $257 million (USPEA 2010, p. 763). The capital investment requirements for both of these systems would be in excess of $4 per gallon of annual capacity. Consistent with these estimates a letter posted on the R Squared Energy Blog reports that Coskata expects a capital cost for their technology of $400 million for a 100 million gallons per year facility (Rapier, 2010).

Prior to investing millions of dollars in a cellulosic biorefinery, prudent investors (including the U.S. government) would expect to have information about the most economical conversion method, approximate investment cost to build a plant, ethanol yield per ton of biomass (ethanol yield depends on feedstock quality and method of conversion), and they would expect assurance that a flow of feedstock that meets the quality standards of the facility will be available at a price that provides a high probability of a positive return on investment.

Progress has been made towards the development of the production and harvest of dedicated energy crops such as switchgrass and miscanthus, and the harvest of crop residues such as corn stover. To-date the standard paradigm for evaluating the economics of cellulosic ethanol has followed the pattern used to evaluate grain ethanol. However, producing, harvesting, storing, and delivering cellulosic biomass and converting it to ethanol is fundamentally different from producing and marketing corn grain, and producing ethanol from grain. The infrastructure for corn grain was well developed prior to implementation of public policies designed to increase the production of fuel ethanol. A similar infrastructure does not exist for cellulosic biomass such as switchgrass.

A number of studies have reported estimates of feedstock production, harvest, storage, and transportation cost (English, Short and Heady 1981; Epplin, 1996; Glassner, Hettenhaus and Schechinger, 1998; Gallagher et al., 2003; Duffy, 2007; Epplin et al., 2007; Brechbill and Tyner, 2008; Graham et al., 2007; Khanna, Dhungana and Brown, 2008; Perrin, 2008; Petrolia, 2008; Vadas, Barnett and Undersander, 2008). In general these studies have not considered quality characteristics other than dry matter and have assumed that the value to a biorefinery of a dry ton of switchgrass would be equal to the value of a dry ton of corn stover independent of month of harvest or length of time in storage. This is one result of the lack of information flow from scientists and engineers conducting the processing research regarding feedstock quality parameters.

Estimating only delivered dry matter cost may be appropriate for a system that requires a feedstock that is relatively homogeneous and easily storable such as corn grain. However, (a) cellulosic biomass feedstock is not homogeneous, (b) ethanol yield depends on feedstock quality and method of conversion, (c) the optimal composition of feedstocks may not be the same across all potential conversion methods, and (d) plant investment cost varies depending on the conversion technology used. Hence, determination of the most efficient system requires a holistic field to products model that simultaneously considers land procurement, feedstock production, harvest, storage, transportation, processing, and the value of final products. Modeling each of the competing conversion systems using a "field to fuel" approach could provide useful information to compare the expected economics of each system and identify unique bottlenecks.

The objective of this study is to determine the ethanol price necessary for a lignocellulosic biorefinery to breakeven. The modeling system enables a determination of the optimal feedstock production, harvest, investment in harvest machines, storage, and transportation strategy, and optimal biorefinery location and size. Given the uncertainty regarding biorefinery capital requirements and the uncertainty regarding the number of gallons of ethanol that could be produced per dry ton by a commercial sized facility, the breakeven ethanol price is computed for 12 different combinations of investment cost and conversion rates.

Procedure/Modeling

The multi-region, multi-period, monthly time-step, mixed integer mathematical programming model described by Tembo, Epplin, and Huhnke (2003), Mapemba et al. (2007), and Hwang (2007) is extended, modified, and enhanced to determine the break-even price of ethanol from 12 alternatives. The objective function is to maximize the net present value of the system with a discount rate of 15 percent subject to a set of constraints including a single biorefinery.

The model is designed and solved to determine the area and quantity of switchgrass harvested by county, the number of harvest machines, and the cost to procure, harvest, store, and transport a flow of switchgrass biomass to an optimally located and optimally sized biorefinery. Binary variables are included in the model to determine the most economical plant location and plant size. Integer variables are used to determine the optimal number of harvest machines.

Background Information of the Model and Current Study

A well-established harvesting and transportation system does not exist for lignocellulosic biorefinery. Hence, Tembo, Epplin, and Huhnke (2003) built a multi-region, multi-period, mixed integer mathematical programming model to identify major cost components for a lignocellulosic biorefinery, reveal opportunities for reducing costs and prioritizing research. Mapemba et al. (2007) extended and modified the model with some updated information. A major difference between Mapemba's and Tembo's model is that Mapemba (2005) designed a harvest unit as an integer and endogenously chosen activity. Mapemba (2005) used the coordinated set of harvest machines designed by Thorsell (2004) to estimate the cost of harvesting. Mapemba (2005) assumed that the number of workdays by month suitable for mowing is also suitable for baling. Hwang (2007) extended the model by recognizing that the number of days suitable for baling in most months is less than the number of days suitable for mowing. Hwang (2007) further extended the model by incorporating separate mowing unit integer activities and separate raking-baling-stacking unit integer activities.

Tembo (2000) and later Mapemba (2005) and Hwang (2007) assumed that switchgrass could be harvested in Oklahoma from July through February of the following year. They assumed that switchgrass yields would be the same for July, August, and September harvests. And, if harvest is delayed post October each additional month will incur a 5% yield loss. But they did not have precise information about switchgrass yield based on month of harvest.

In addition, they assumed that in post establishment years, a fixed level of nitrogen fertilizer would be required independent of harvest month. Tembo (2000), Mapemba (2005), and Hwang (2007) assumed that in post establishment years 25, 75, and 80 pounds of nitrogen fertilizer, respectively, would be applied per acre per year to the established switchgrass independent of harvest month. However, protein (nitrogen) levels are relatively high in grasses cut in mid-season, and optimal nitrogen fertilizer levels are greater for switchgrass harvested in July relative to switchgrass harvested in October (Chapter I). Late in the growing season, nitrogen translocates from the above ground foliage to the plant's crown and rhizomes. If harvest is delayed until after first frost and the initiation of senescence, nitrogen will have translocated, reducing the quantity of nitrogen fertilizer needed for biomass production in subsequent years. The current study considers this issue and other updated information and extends, modifies, and enhances the Hwang version of the Mapemba and Tembo model in several respects.

First, in the present study, data produced in a designed multiyear field trial are incorporated in the model as an estimate of switchgrass harvestable yield response to nitrogen fertilizer for alternative harvest months. Second, this study accounts for differences in nitrogen requirements dependent on months of harvest for switchgrass and incorporates it in the model while estimating cost of switchgrass production. Third, Tembo (2000), Mapemba (2005) and Hwang (2007)'s models assumed expected life of the biorefinery is one to 15 years and that the biorefinery would start operation from the first day. The current study assumes that plant investment costs would occur in year zero and biomass production, harvest, and delivery, plant operation, and ethanol production begins in year one and continues through year 20.

In addition, Tembo (2000), Mapemba (2005) and Hwang (2007) used the biomass transportation cost regression equation reported by Bhat, English, and Ojo (1992). For the present study, a feedstock transportation cost equation (Chapter II) was estimated from data provided by Wang (2009).

Harvest machines for cutting units and for raking-baling-stacking units were updated and machinery ownership and operation costs were estimated. The model differs from previous models (Tembo 2000); Mapemba 2005; Hwang 2007) in that switchgrass production is modeled to compete for both improved pasture land and cropland. Since Oklahoma has 4.7 million acres of improved pasture land and switchgrass is a perennial grass that is naturally drought resistant and grows on marginal land, there is potential to grow switchgrass on improved pasture land. In addition, in Oklahoma, on average, cropland cash rental rates are greater than pasture land cash rental rates.

Model

In this section, a mathematical description of the model, data sources and assumptions are presented. Descriptions of all indices, parameters and variables used in the model are summarized in the list of symbols at the beginning of this dissertation. The multi-region, multi-period, monthly time-step, mixed integer mathematical programming model was solved by the generalized algebraic modeling system (GAMS) software using the CPLEX solver. The model includes about 46,101 activities and 8,850 equations.

The objective function of the model is to maximize net present value of the industry:

$$(3.1) \quad \max_{\substack{Q^E,A,XS,XSP,XST,\\ HUB,HUM}} NPV$$
$$= \left[\left\{ \sum_{m=1}^{M} \left(\sum_{j=1}^{J} \sum_{s=1}^{S} \rho^E Q^E_{msj} - \sum_{i=1}^{I} \sum_{l=1}^{L} \lambda_l A_{iml} - \sum_{i=1}^{I} \alpha_m A_{im} - \sum_{i=1}^{I} \gamma_m A_{im} - \sum_{I=1}^{I} \Gamma * XSP_{im} - \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{s=1}^{S} \tau_{ij} * XST_{ijsm} \right) - \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{ft=1}^{FT} OMC_{s,ft} \beta_{js} - \omega HUC - \varpi HUB \right\} * PVAF \right] - \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{ft=1}^{FT} AFC_{s,ft} \beta_{js} \ .$$

This study assumes a market discount rate of 15 percent (Kaylen et al., 2000; Tembo, 2000). In addition, it is assumed that plant investment costs would occur in year zero. Biomass harvest and delivery, plant operation, and ethanol production begins in year one and continues through year 20. Activities in years one through 20 are assumed to be identical. Hence, the annual net benefit can be treated as an annuity. The model uses this assumption and defines NPV with the present value of annuity factor (PAVF):

$$(3.2) \qquad PAVF = \frac{(1+r)^T - 1}{r(1+r)^T}.$$

"The model includes a lot of details. Hence, the simplification implied by assuming that the years are identical is necessary as a check on dimensionality, without much loss of generality" (Tembo 2000, p. 44).

Inside the model (equation 3.1) the price of ethanol (ρ^E) is parameterized until the net present value of the industry is equal to zero. At that point the breakeven price of ethanol is determined and least-cost estimates are found. For each plant location and size, average fixed cost ($AFC_{s,ft}$) and operating and maintenance cost ($OMC_{s,ft}$) are charged to the objective function only if the corresponding binary variable (β_{js}) attains a value of one. For the base model, biorefinery investment costs of $189.5, $275, and $400 million were assumed for the 25, 50, and 100 million gallons per year facilities, respectively. Given the uncertainty regarding capital requirements, models are also solved with these values halved ($95, $138, and $200 million) and doubled ($284, $413, and $600 million). Each of these three capital requirements scenarios is modeled for four biomass to ethanol conversion rate alternatives: 60, 80, 100, and 120 gallons of ethanol per dry ton of biomass. A total of 12 capital requirement-conversion rates are considered.

In the objective function, λ_l refers to feedstock production cost that includes the cost associated with establishment, maintenance and land rent of switchgrass biomass by land category but excludes cost of fertilizer. The cost of nitrogen and cost of phosphorus in the form of phosphorus oxide (P_2O_5) were included separately from the cost of feedstock production to account for differences in fertilizer requirements across harvest months. Whereas, previously (Tembo, 2000; Mapemba et al. 2007; and Hwang 2007) the cost of nitrogen was included in the λ_l term.

In the model, α_m refers to the cost of applied nitrogen in dollars per acre ($\mathrm{NCOST_m}$) which is a function of nitrogen application depending on month of harvest:

$$\mathrm{NCOST_m(\$/acre) = P^n * NIT_m} \tag{3.3}$$

where $\mathrm{P^n}$ is the price of nitrogen in $/pound and $\mathrm{NIT_m}$ is the level of nitrogen (pounds per acre) which depends on the month in which the switchgrass was harvested in the prior growing season. Hence, the total cost of nitrogen is:

$$\mathrm{NCOST(\$)} = \sum_{i=1}^{I}\sum_{m=1}^{M}(\mathrm{NCOST_m * A_{im}}). \tag{3.4}$$

In the model, γ_m refers to the cost of P_2O_5 ($PCOST_m$) which is a function of application of P_2O_5 which depends on the month in which the switchgrass was harvested in the prior growing season. Mathematically,

$$\text{(3.5)} \qquad PCOST_m(\$/acre) = P^P * PIT_m$$

where P^p is the price of P_2O_5 in \$/pound and PIT_m is the level of P_2O_5 (pounds per acre). Hence, the total cost of P_2O_5 is:

$$\text{(3.6)} \qquad PCOST(\$) = \sum_{i=1}^{I}\sum_{m=1}^{M}(PCOST_m * A_{im}).$$

In the model, Γ is the biomass storage cost per ton per month. It is assumed that shipment of feedstock can be done in any of the twelve months of the year. Harvested feedstock can be transported directly from the field to the plant or can be placed in field storage for transport and use in later months.

Model Constraints

The model is maximized subject to a set of constrains. The definition and description of the model constraints draws heavily from Tembo (2000, p. 39-40), Mapemba (2005, p. 68-72), and Hwang (2007, p. 48-54).

The land constraint (equation 3.7) requires that the total harvested acres in each county may not exceed the number of acres available for harvest in the county. BP_{il} is the proportion of land in acres that can be harvested for biomass feedstock by land category. BP_{il} includes $BPROPP$ and $BPROP1$ which represent the proportion of harvestable acres from cropland and from improved pasture land, respectively. In this model, $BPROP$ and $BPROP1$ restrict land use to no more than 10% of cropland acres in each county and no more than 10% of improved pasture land acres in each county, respectively:

(3.7) $$\sum_{m=1}^{M} A_{im-} \sum_{l=1}^{L} BP_{il}\, LAND_{il} \leq 0, \qquad \forall_{i}.$$

A yield balance equation is included to compute the amount of biomass production from the harvested acres. Equation (3.8) states that the amount of switchgrass biomass harvested is equal to the available biomass in the field (less any field losses):

(3.8) $$XS_{im} = YAD_m A_{im} BYLD_i, \qquad \forall_{i}.$$

The yield adjustment factor (YAD_m) is used to adjust yield from the expected maximum yield depending on harvest month. The YAD_m is equal to one for months in which harvestable yield is expected to be at a maximum level. If harvest is conducted early or delayed until winter, the *YAD* level is less than one and reflects the consequences of not harvesting during a month when switchgrass harvestable yield is at its greatest level. For the months of April, May and June the YAD_m is set equal to 0 indicating no harvest in those months. Available biomass in the field is computed based on YAD_m, number of acres harvested, and the maximum expected yield for the county.

Equation (3.9) imposes a restriction that no acres will be harvested in a month when the yield adjustment factor is equal to zero:

(3.9) $$A_{im} = 0 \; if \; YAD_m = 0, \qquad \forall_{i}, m.$$

Equation (3.10) states that at each source (county) and in each month, the sum of biomass transported to the plant location from production regions and biomass stored should be equal to the sum of current production and the usable portion of stored biomass.

(3.10) $$\sum_{j=1}^{J}\sum_{s=1}^{S} XST_{ijsm} + XSS_{im} - \theta_i XSS_{im-1} + XS_{im} = 0, \qquad \forall_{i,m}\,.$$

where θ_i is the the proportion of switchgrass which is usable following one month of in-field storage at production region *i*. θ_i is calculated by subtracting the monthly deterioration rate for switchgrass when stored at production region *i*.

The following constraint states that total biomass harvested should be equal to the total quantity transported to the plant plus the total lost in storage:

(3.11) $$\sum_{m=1}^{M} XS_{im} - \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{m=1}^{M} XST_{ijsm} - (1-\theta_m)\sum_{m=1}^{M} XSS_{im} = 0, \qquad \forall_{i}\,.$$

To ensure total supply equal to the total demand equation (3.12) states that the total amount of switchgrass biomass harvested and total quantity of biomass removed from storage in each month should be equal to the amount of transported biomass to the plant from production region and the quantity of biomass placed in storage at the plant:

(3.12) $$\sum_{i=1}^{I} XS_{im} + \sum_{i=1}^{I} XSN_{im} - \sum_{\boldsymbol{i=1}}^{\boldsymbol{I}}\sum_{\boldsymbol{j=1}}^{\boldsymbol{J}}\sum_{\boldsymbol{s=1}}^{\boldsymbol{S}} XST_{\boldsymbol{ijsm}} - \sum_{i=1}^{I} XSP_{im} = 0, \qquad \forall_{\ m}\,.$$

Equation (3.13) states that the sum of harvest units for cutting used in any month can not exceed the total number of cutting harvest units as determined endogenously by the model:

(3.13) $$\sum_{i=1}^{I} XShuc_{im} - HUC \leq 0, \qquad \forall_{m}\,.$$

Equation (3.14) is similar to equation (3.13) in that it restricts the sum of harvest units for raking-baling-stacking used in each month from exceeding the total number of raking-baling-stacking harvest units endogenously determined by the model:

(3.14) $$\sum_{i=1}^{I} XShub_{im} - HUB \leq 0, \qquad \forall_m .$$

Equations (3.15) and (3.16) ensure that the quantity of biomass harvested in each producing county and month may not exceed the combined harvesting capacity of the number of harvest units for cutting, and number of units for raking-baling-stacking as determined by the model:

(3.15) $$XS_{im} - XShuc_{im} CAPHUC_{im} \leq 0, \qquad \forall_{i,m},$$

(3.16) $$XS_{im} - XShub_{im} CAPHUB_{im} \leq 0, \qquad \forall_{i,m} .$$

Equation (3.17) connects biomass plant processing capacity to the binary variable:

(3.17) $$Q^E_{jsm} - CAP_S \beta_{js} \leq 0, \qquad \forall_{j,s,m} .$$

If $\beta_{js} = 1$ then $CAP_S \beta_{js} = CAP_S$, the processing capacity upper bound in gallons of ethanol, and the total production at each plant in that month will be bounded by $0 \leq Q^E_{jsm} \leq CAP_S$. If $\beta_{js} = 0$, then $CAP_S \beta_{js} = 0$ and since Q^E_{jsm} cannot be negative, hence it is equal to 0.

Similar to equation (3.17), equation (3.18) links biomass storage capacity to the binary variables:

(3.18) $$XSS_{jm} - CAS_S \beta_{js} \leq 0, \qquad \forall_{j,s,m} .$$

If $\beta_{js} = 1$ then $CAP_S \beta_{js} = CAP_S$ and the total quantity of stored biomass at the biorefinery will be bounded by $0 \leq XSS_{jm} \leq CAP_S$. If $\beta_{js} = 0$, then $CAP_S \beta_{js} = 0$ and XSS_{jm} cannot be negative, hence it is equal to 0. No storage upper bounds are assumed for storage in the field.

Equation (3.19) imposes that the total biomass processed or stored at the biorefinery should be equal to the total harvested biomass available:

$$\sum_{j=1}^{J} XST_{ijsm} + \theta_j XSS_{jm-1} - XSS_{jsm} - XPP_{jsm} = 0, \qquad \forall_{j,m,s} . \tag{3.19}$$

Equation (3.20) states that the total biomass delivered from each feedstock production county to the biorefinery equals the sum of processed biomass and on-site storage losses:

$$\sum_{i=1}^{I}\sum_{m=1}^{M} XST_{ijsm} - (1-\theta_m)\sum_{m=1}^{M} XSS_{jsm} - \sum_{m=1}^{M} XPP_{jsm} = 0, \quad \forall_{\ j,s} . \tag{3.20}$$

Equation (3.21) restricts ethanol production to the product of the corresponding transformation coefficient and the quantity of biomass used. The inequality allows for production losses:

$$Q^{E}_{jsm} - \mu^{E} XPP_{jsm} \leq 0, \qquad \forall_{j,s,m} . \tag{3.21}$$

Equation (3.23) places an upper bound on the number of biorefineries that can be built, assumed here to be equal to one.

$$\sum_{j=1}^{J}\sum_{s=1}^{S} \beta_{js} \leq 1 . \tag{3.23}$$

The model is provided with three possible plant sizes: small, medium, and large, the upper bound is one plant among six potential plant locations. As modeled, processing costs per gallon are lower for the large plant. However, since feedstock transportation costs are a function of miles, and since a larger plant requires a larger average transportation distance, delivered feedstock costs are greater for the larger plant. The model can be used to determine the tradeoff between plant size and transportation costs.

Equation (3.24) restricts values of the binary variable to the set of zero and one:

(3.24) $$\beta_{js} \in \{0,1\}.$$

Equation (3.25) constrains the model from negative quantities of the choice variables (acres harvested, biomass produced, transported, stored, and ethanol produced) (nonnegativity condition).

(3.25) $$A_{im},\ XS_{im}, XSP_{im}, XST_{ijsm}, XSS_{im}, XPP_{jsm}, q_{jsm}^{E} \geq 0.$$

Equation (3.26) restricts the number of the harvest units for cutting and raking-baling-stacking to integer values.

(3.26) HUC and HUB are nonnegative integer variables.

Data Descriptions and Assumptions

The study is based on the assumption that a biorefinery would depend entirely on switchgrass as a single feedstock and would be located in Oklahoma. USEPA (2010) estimates that by 2022 eleven cellulosic ethanol biorefineries that use switchgrass as the feedstock will be operating in Oklahoma. The model is limited to the eastern 57 of Oklahoma's 77 counties as production regions (Chapter II, Figure II-2). Tall grasses such as switchgrass are not common in the native prairies of the westernmost 20 counties. Field trials would be required to determine if pure stands of switchgrass would persist on the soils and in the climate of these counties (Kakani 2009; Wu 2009). Six candidate biorefinery locations are included. These locations are Canadian, Garfield, Okmulgee, Payne, Pontotoc, and Washington counties and are selected considering biomass relative density and availability of road infrastructure.

Switchgrass biomass yield estimates for each of 57 counties for each of nine harvest months were obtained from several sources (Graham, Allison and Becker 1996; Fuentes and Taliaferro 2002; Wu 2009, Chapter I and II). Based on the findings reported in Chapter II the strategy of extending harvest over many months is economically preferable to a strategy of harvesting only in peak yield harvest months for switchgrass. Hence, in this study it is assumed that the switchgrass harvest season may begin in July and extend through March. Harvest during April, May, and June are not permitted by the model since it is anticipated that harvest during these months would damage plant growth for subsequent years. Maximum expected yield is obtained by harvesting in either September or October. Expected yield from harvest in July is 79 percent of maximum (chapter I). If switchgrass is left to stand in the field, dry matter losses of five percent per month are expected from November through March.

It is assumed that fields that are harvested in July are expected to require 80 pounds per acre of nitrogen to achieve the plateau yield, whereas fields harvested during and between October and March are expected to require only 63 pounds per acre (Chapter I). Estimates of the proportion of potential switchgrass expected yield and estimates of the level of nitrogen (pounds per acre) applied in the spring required to achieve the plateau yield depending on harvest month were obtained from Chapter I and Chapter II (Table II-2, Figure III-1 and Figure III-2).

In the model, switchgrass production is restricted to two land classes: cropland and improved pasture land. Data from the Census of Agriculture were used to determine acres of cropland and improved pasture (USDA, 2002). In a given county, the expected switchgrass yields were assumed to be the same on improved pasture land as on cropland.

This assumption follows from the finding that switchgrass yield is limited more by available moisture and the length of the growing season than by soil quality (Kakani 2009; Wu, 2009).

Restrictions are included in the model to limit switchgrass production in each county to no more than ten percent of the county's cropland and no more than ten percent of the county's improved pasture land. Another assumption is that the use of this cropland and improved pasture land can be acquired at a long-term lease rate of $60 and $40 per acre per year, respectively. The average 2005-09 cropland cash rental for Oklahoma non-irrigated cropland ranged from $28-$31 per acre, and the average 2005-09 pasture land cash rental for Oklahoma ranged from $8.50-$10.50 per acre (USDA, 2009). The assumptions of $60 and $40 per acre for cropland and pasture land lease rates used in the study are made to account for the need to entice land owners to enter into a long-term lease that would be necessary for the perennial grass and to recognize that land lease rates in the vicinity of a biorefinery would increase in response to the plant's existence. Switchgrass production cost estimates are based on establishment and maintenance budgets presented in Chapter I.

In this study, the harvest unit concept based on the study by Thorsell et al. (2004) and Hwang (2007) was revised and used to determine the cost of switchgrass harvest machines. Expert opinions (AGCO Corporation 2010; ASABE 2006; Huhnke 2010; Lazarus and Smale 2010; Stinger Ltd. 2010) were used to budget the specific windrower, rake, baler and stacker. The annual ownership and the operating cost of a cutting unit is estimated to be $106,463. This value includes ownership costs (depreciation, interest on average investment, taxes, insurance) and operating costs (fuel, oil, repairs, and lubricants) for a windrower equipped with a rotary header, and the cost of labor.

The annual ownership and the operating cost of a raking-baling-stacking harvest unit for a nine-month harvest season is estimated to be $545,516. If the unit is only used for two months, the annual ownership and operating cost is estimated to be $169,866. The number of harvest days available for cutting and baling in each month for each of the 57 counties (based on various weather variables and historical Oklahom Mesonet weather data) were obtained from Hwang et al. (2009). Details of methods used to obtain harvest cost estimates are presented in Chapter II.

Previous studies (Tembo 2000; Mapemba 2005; Hwang 2007) used the biomass transportation cost regression equation reported by Bhat, English, and Ojo (1992). For the present study, a feedstock transportation cost equation was estimated from data provided by Wang (2009). Wang (2009) estimated the costs to transport switchgrass from fields in Tennessee to a biorefinery located in Tennessee. Wang (2009) assumed that a semi-tractor trailer could transport 16 dry tons of rectangular solid bales per load. The equation used to calculate biomass transportation costs for a 16 dry ton truck load is:

(3.27) $$TRC_{ij} = 12.78 + 1.72d_{ij}$$

where TRC_{ij} is the estimated transportation cost in dollars per 16 dry ton truck load for transporting biomass from the supplying county *i* to the biorefinery plant location j; d_{ij} is the round-trip distance in miles. Feedstock transportation costs per ton are calculated by dividing TRC_{ij} by the truck capacity of 16 dry tons. Based on a round trip distance of 75 miles, the average transportation cost per load is estimated to be $141.78. The estimated cost per dry ton is $8.86.

The biorefinery is assumed to operate 350 days per year. Storage losses at the biorefinery and in the field are assumed to be one percent per month. Another assumption is that bales stored in the field would be covered with a plastic tarp. The cost of field storage is estimated to be $2 per ton regardless of the number of months the material is in storage.

No feedstock quality attribute other than dry matter is considered. It is assumed that switchgrass dry matter would be of equivalent value to the biorefinery independent of harvest month and time in storage. For the base model, a conversion rate of 100 gallons of ethanol per dry ton of switchgrass is assumed. Sensitivity analysis is conducted by solving the model with alternative conversion rates of 60, 80 and 120 gallons per dry ton.

The model is designed to consider three plant sizes: 25, 50 and 100 million gallons per year. For the base model, biorefinery investment costs of $189.5, $275 and $400 million are assumed for the 25, 50 and 100 million gallons per year facilities, respectively. These estimates of capital required are $7.58, $5.50 and $4.00 per gallon of annual capacity for the three sizes. Values assumed for selected parameters are reported in Table III-2.

Annual plant operation and maintenance costs including the cost of labor, utilities, chemicals, other required variable inputs, taxes, repairs, and insurance are assumed to be $0.75 per gallon of production. USEPA (2010, p. 751) estimates a cost for these inputs of approximately $0.68 per gallon. The value of co-products was assumed to be equal to disposal cost.

Results

For each of the 12 capital requirement-conversion rates considered, the model selects the 100 million gallons per year biorefinery rather than either the 25 or 50 million gallons per year facility. And, the model selects Pontotoc County for the plant location rather than any of the other five alternative locations. In the region, the cost economies of the larger processing plant offset the additional transportation costs that result when procuring feedstock from greater distances.

The Breakeven Price of Ethanol

Table III-3 includes breakeven ethanol prices for each of the 12 capital requirement-conversion rates considered. Table III-4 includes results of total biomass harvested, total number of acres harvested, and estimated delivered cost of feedstock. For a capital requirement of $400 million and a conversion rate of 100 gallons of ethanol per dry ton, the breakeven ethanol price for the 100 gallons per year biorefinery is $1.93 per gallon. The breakeven price of ethanol reduces by $0.32 per gallon if capital requirements decrease to $200 million. Similarly, increasing plant investment cost from $400 to $600 million, increases the breakeven price of ethanol by $0.32 per gallon. This $0.32 is the $2 per gallon investment cost difference amortized over 20 years at the assumed discount rate of 15 percent.

For a conversion rate of 60 gallons per dry ton, 1.7 million tons of biomass is required (table III-4). More than 349,000 acres would be required to produce the feedstock. However, for a conversion rate of 120 gallons per dry ton, the model selects 171,203 acres to produce the 0.85 million required tons. More biomass is harvested than processed to compensate for storage losses.

Costs Incurred to Produce a Gallon of Ethanol

Table III-4 shows the estimated feedstock delivered cost to the optimally located biorefinery for each of the four biomass to ethanol conversion rates. As the conversion rate increases from 60 to 80 to 100 to 120 gallons of ethanol per ton, the total cost of delivered feedstock decreases from $57.93 to $55.99 to $54.04 to $53.46 per dry ton, respectively. These costs include land rent, establishment, fertilizer, harvest, storage, and transportation. Transportation and harvest cost comprise the largest component of feedstock delivered cost. As the conversion rate increases from 60 to 80 to 100 to 120 gallons per ton, transportation costs decrease from $0.35 to $0.23 to $0.18 to $0.14 per gallon of ethanol. Transportation costs account for 30 to 35 percent of the delivered feedstock cost. Harvest costs account for 23 to 25 percent of the delivered feedstock cost.

For a capital requirement of $400 million and a conversion rate of 100 gallons of ethanol per dry ton, the breakeven ethanol price is $1.93 per gallon. This includes $0.09 (4.80 percent of the $1.93) for land rental, $0.13 (6.73 percent) for field cost, $0.14 (7.03 percent) for harvest, $0.004 (0.21 percent) for field storage, $0.18 (9.27 percent) for transporting the biomass from the field to the biorefinery, $0.75 (38.85 percent) for plant operation and maintenance and $0.64 (33.10 percent) for capital recovery (table III-5).

Figure III-3 includes cost components for the breakeven ethanol prices of $1.61, $1.93 and $2.25 per gallon with capital requirement of $200, $400, and $600 million respectively, for a conversion rate of 100 gallons per ton**.** Biorefinery construction, operation, and maintenance costs constitute the major cost component. As the conversion rate increases from 60 to 80 to 100 to 120 gallons of ethanol per ton for a plant with capital requirement of $400 million, feedstock transportation costs and the total cost of delivered feedstock decreases. Figure III-4 shows cost components for the four conversion rates for the breakeven ethanol prices of $2.36, $2.09, $1.93 and $1.84 per gallon. Results clearly show that the cost of constructing and operating the plant, and the conversion rate (ethanol per dry ton of feedstock) play crucial roles in determining the breakeven price of ethanol. These findings suggest that efforts to reduce cost should focus on conversion rate and on the cost of biorefinery construction, operation, and maintenance.

Breakeven Price of Ethanol, Price of Unleaded Gasoline,

and Price of Crude Oil

Ethanol contains less energy (75,700 Btu) per gallon than unleaded gasoline (115,000 Btu) (U.S. Department of Energy 2009). When ethanol is blended with gasoline at levels of ten percent or less, it has value as an oxygenate in addition to its energy value. However, when used in greater proportions in engines with compression ratios designed for unleaded gasoline, the lower Btu content results in a proportionately lower mileage. If the EISA mandates are achieved, ethanol production will exceed the quantity required for ten percent blends. At this level of use the marginal value of ethanol could be expected to be based on its energy content relative to gasoline. By this measure, the estimated $1.93

breakeven ethanol price would be equivalent to a wholesale price of $2.93 per gallon for unleaded gasoline.

A simple ordinary least squares regression of the annual price of gasoline (U.S. Energy Information Administration, 2010a) on the price of crude oil (U.S. Energy Information Administration, 2010b) (1989 to 2009) results in the following equation: wholesale gasoline ($ per gallon) = 0.05 + 0.0259 x crude oil price ($ per barrel). By this measure for a crude oil price of $111 per barrel the expected wholesale price of gasoline is $2.93 per gallon (table III-5). Based strictly on energy equivalence, ethanol priced at $1.93 would be cost completive when the price of crude oil exceeds $111 per barrel.

Summary and Conclusion

The U.S. Energy Independence and Security Act of 2007 mandates the production of 16 billion gallons of cellulosic biofuels by 2022. But, no commercial sized facilities were operating in 2009. Hence, it seems reasonable to conclude that development of a commercially viable system for production of cellulosic ethanol has not progressed as rapidly as anticipated. Previous studies identified several methods or technical categories for producing ethanol from cellulose. But, desirable feedstock properties, biomass to biofuel conversion rate, and investment required in plant and equipment differs depending on which of several competing technologies is used.

Determination of the most efficient system requires a holistic field to products model that simultaneously considers land procurement, feedstock production, harvest, storage, transportation, processing, and the value of final products. Modeling each of the competing conversion systems using a “field to fuel” approach could provide useful information to compare the expected economics of each system and identify unique bottlenecks.

The objective is to determine the breakeven ethanol price for a cellulosic biorefinery. A comprehensive mathematical programming model that encompasses the chain from land acquisition to ethanol production was constructed and estimated. Given the uncertainty regarding biorefinery capital requirements and the uncertainty regarding the number of gallons of ethanol that could be produced per dry ton by a commercial sized facility, the breakeven ethanol price is computed for 12 different combinations of investment cost and conversion rates. A multi-region, multi-period, monthly time-step, mixed integer mathematical programming model is constructed. The objective function is to maximize the net present value of the system subject to set of constraints.

For a capital requirement of $400 million for a 100 million gallons per year plant and a conversion rate of 100 gallons of ethanol per dry ton, the breakeven ethanol price is $1.93 per gallon: $0.22 for land rental, switchgrass production, and field storage; $0.14 for feedstock harvest; $0.18 for feedstock transportation; $0.75 for biorefinery operation and maintenance; and $0.64 for biorefinery investment. For the $1.93 per gallon breakeven ethanol price, the biorefinery construction, operation, and maintenance cost account for around 72 percent of the total cost and feedstock cost accounts for only 28 percent. Results clearly show that the cost of constructing and operating and conversion rate (ethanol per dry ton of feedstock) plays a crucial role while determining the breakeven price of ethanol. These findings suggest that efforts to reduce cost should focus on conversion rate and on the cost of biorefinery construction, operation, and maintenance.

Limitation of the Study and Need for Further Research

In this study, the breakeven ethanol price is computed for 12 different combinations of investment cost and conversion rates since biorefinery capital requirements and the number of gallons of ethanol that could be produced per dry ton by a commercial sized facility depending on conversion technology is still unknown. When data on investment cost and biomass to biofuel conversion rate for alternative conversion systems become available, additional research can be done to estimate a comprehensive holistic model for other alternative conversion systems to compare the economics of the different alternative conversion systems and to determine which system is most likely to be successful in fulfilling the EISA mandates.

In the current study, no feedstock quality characteristics other than dry matter were considered. Feedstock quality attributes in addition to dry matter may be important depending on which conversion technology is used. Biomass is a mix of different components; three basic components are lignin, cellulose and hemicelluloses. A gasification process may result in greater yields of ethanol per unit of input material because it has potential to convert more of the carbon compounds into biofuels. On the other hand, for an enzymatic hydrolysis process, only the cellulose (structural glucan) and hemicellulose (xylan+others) are partially converted after being broken down to sugars. The lignin and other unconverted carbon compounds end up as waste. A biorefinery using enzymatic hydrolysis could be expected to be concerned about the proportion of glucan and xylan in the feedstock. If data becomes available regarding these attributes for each potential feedstock for harvest and storage situations likely to be encountered, the model could be enhanced to determine the most economical conversion technology for a biorefinery and a more precise estimate of the breakeven ethanol price.

One limitation of the study is the yield and nitrogen adjustment factors used to account for the yield and nitrogen differences by month was based on Taliaferro's field experiments conducted in Stillwater. It was assumed that the yield adjustment factors and the nitrogen requirements by month were the same across all 57 counties included in the study and on both cropland and improved pasture land. Additional switchgrass yield response to nitrogen studies would be required in other counties to determine if the findings are robust. Additional harvest studies would also be required to determine if application of the same yield adjustment factors across all counties is justified.

Another limitation is related to the price of diesel used in the model. To estimate the operating cost of a harvest unit, a diesel price of $2.57 per gallon (USDA, NASS, 2009) was assumed. The transportation cost equation used in the model is based on data provided by Wang (2009) wherein she assumed a diesel price of $1.83 per gallon. Additional modeling work would be required to rectify these inconsistencies.

The prices of gasoline, diesel, crude oil, and ethanol are highly correlated. To measure the relationship of the price of diesel relative to the price of crude oil a regression equation was estimated. Based on 15 years of annual observations and data from the U.S. Energy Information Administration (2010c), the price of diesel fuel ($ per gallon) is equal to -0.07 + 0.03 x crude oil price ($ per barrel). By this measure, the $2.57 per gallon for diesel assumed for harvest machines is consistent with a crude oil price of $89 per barrel. The $1.83 per gallon used to estimate the transportation cost equations would be consistent with a crude oil price of $65 per barrel. Previously it was noted that for a crude oil price of $111 per barrel the expected wholesale price of gasoline is $2.93 per gallon which is equivalent to the estimated breakeven price of ethanol of $1.93 per gallon. Additional modeling work would be required to endogenously adjust the diesel prices in the model with the breakeven ethanol price.

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APPENDIX A FOR CHAPTER III: TABLES AND FIGURES

Table III-1: Published Estimates of Expected Biomass to Ethanol Conversion Rate and Expected Capital Cost Required to Construct a Commercial-Scale Biorefinery

Biomass to Ethanol Conversion Rate			
Source	Ethanol Yield (gal/dry tons)	Type of Feedstock	Conversion Technology
USEPA (2010) (Purdue University Study)	72	Corn stover	Enzymatic Hydrolysis
USEPA (2010)	90	Corn stover	Enzymatic Hydrolysis
Coskata (2010)	100	Any carbon-containing input materials including switchgrass	Biological fermentation /gasification technology
Schmer et al. (2008)	91	Switchgrass	NR[a]
U.S. Department of Energy (2010) (Projection for 2012)	89.9	Corn stover	Dilute Acid Pretreatment, Enzymatic Hydrolysis and Co-Fermentation
USEPA (2010) (Projection for 2022)	94	Corn stover	Enzymatic Hydrolysis
Expected Capital Cost Required to Construct a Commercial-Scale Biorefinery			
Source	Expected Capital Cost ($ millions)	Annual Capacity (million gal)	Conversion Technology
USEPA (2010) NERL projected	232	56	Biochemical conversion
USEPA (2010) (NERL projected)	257	63	Thermochemical
Rapier (2008) (Coskata reported)	400	100	Gasification/Biological fermentation

[a] Not reported in the study

Table III-2: Values for Selected Variables for the Twelve Alternatives

	Alternatives											
Item	Expected capital cost				Low capital cost				High capital cost			
Biorefinery capital investment												
Small plant (million $)	189	189	189	189	94.5	94.5	94.5	94.5	283.5	283.5	283.5	283.5
Medium plant (million $)	275	275	275	275	137.5	137.5	137.5	137.5	412.5	412.5	412.5	412.5
Large plant (million $)	400	400	400	400	200	200	200	200	600	600	600	600
Conversion rate (gallons of ethanol/dry ton)	60	80	100	120	60	80	100	120	60	80	100	120
Operation & maintenance cost ($/gallon)	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Biorefinery processing capacity												
Small plant (million gallons/year)	25	25	25	25	25	25	25	25	25	25	25	25
Medium plant (million gallons/year)	50	50	50	50	50	50	50	50	50	50	50	50
Large plant (million gallons/year)	100	100	100	100	100	100	100	100	100	100	100	100
Project life (years)	20	20	20	20	20	20	20	20	20	20	20	20
Discount rate (%)	15	15	15	15	15	15	15	15	15	15	15	15
Land lease rate ($/acre/year)												
Cropland	60	60	60	60	60	60	60	60	60	60	60	60
Improved pasture land	40	40	40	40	40	40	40	40	40	40	40	40
Maximum proportion of land leased per county (%)												
Cropland	10	10	10	10	10	10	10	10	10	10	10	10
Improved pasture land	10	10	10	10	10	10	10	10	10	10	10	10
Potential plant locations (number)	6	6	6	6	6	6	6	6	6	6	6	6
Production regions (number)	57	57	57	57	57	57	57	57	57	57	57	57
Harvest months per year	9	9	9	9	9	9	9	9	9	9	9	9

Note: The model considered 57 Oklahoma counties as production regions. Switchgrass is the only feedstock considered.

Table III-3: Estimated Ethanol Breakeven Price ($ per gallon) for Three Levels of Capital Investment Requirements and Four Biomass to Ethanol Conversion Rates

	Conversion Rate of Ethanol (Gallons/dry ton)			
Investment Cost (millions $)	60	80	100	120
200	2.04	1.77	1.61	1.52
400	2.36	2.09	1.93	1.84
600	2.68	2.41	2.25	2.16

Note: Breakeven prices of ethanol are defined to be the price at which the net present value of the biorefinery system is equal to zero.

Table III-4: Biomass Harvested, Acres Harvested, and Estimated Cost of Delivered Feedstock for Four Biomass to Ethanol Conversion Rates

Conversion Rate of Ethanol (gallons/dry ton)	Biorefinery Size (gallons/year)	Total Biomass Harvested (dry tons)	Total Land Harvested (acres)	Total Cost of Delivered Feedstock ($/ton)
60	100,000,000	1,691,686	349,184	57.93
80	100,000,000	1,268,872	260,508	55.99
100	100,000,000	1,015,350	205,698	54.04
120	100,000,000	846,041	171,203	53.46

Note: For a given conversion rate, the optimal biorefinery size, total biomass harvested, and total number of acres harvested, are the same regardless of investment cost
.

Table III-5: Components of Cellulosic Ethanol Production Cost*.

Investment Cost (million $)	Conversion Rate of Ethanol (gallons per dry ton)	Land Rent	Field Costs	Field Storage Costs	Harvest Costs	Transportation Costs	Plant Costs[a]	Total costs
		($ per gallon)						
200	60	0.17	0.22	0.01	0.22	0.35	1.07	2.04
		(8.24%)	(10.82%)	(0.33%)	(11.04%)	(17.01%)	(52.56%)	(100%)
200	80	0.12	0.17	0.005	0.17	0.23	1.07	1.77
		(6.95%)	(9.61%)	(0.29%)	9.63%)	13.08%)	(60.44%)	(100%)
200	100	0.09	0.13	0.004	0.14	0.18	1.07	1.61
		(5.75%)	(8.01%)	(0.25%)	(8.43%)	(11.12%)	(66.43%)	(100%)
200	120	0.08	0.11	0.003	0.12	0.14	1.07	1.52
		(5.03%)	(7.26%)	(0.23%)	(7.60%)	(9.29%)	(70.60%)	(100%)
400	60	0.17	0.23	0.01	0.22	0.34	1.39	2.36
		(7.10%)	(9.89%)	(0.29%)	(9.51%)	(14.45%)	(58.76%)	(100%)
400	80	0.12	0.17	0.005	0.17	0.23	1.39	2.09
		(5.88%)	(8.14%)	(0.24%)	(8.16%)	(11.08%)	(66.49%)	(100%)
400	100	0.09	0.13	0.004	0.14	0.18	1.39	1.93
		(4.80%)	(6.73%)	(0.21%)	(7.03%)	(9.27%)	(71.95%)	(100%)
400	120	0.08	0.12	0.003	0.12	0.14	1.39	1.84
		(4.13%)	(6.51%)	(0.18%)	(6.24%)	(7.63%)	(75.31%)	(100%)
600	60	0.17	0.22	0.01	0.22	0.35	1.71	2.67
		(6.27%)	(8.23%)	(0.25%)	(8.40%)	(12.95%)	(63.89%)	(100%)
600	80	0.12	0.17	0.005	0.13	0.23	1.71	2.41
		(5.10%)	(7.06%)	(0.21%)	(7.08%)	(9.61%)	(70.94%)	(100%)
600	100	0.09	0.13	0.004	0.14	0.18	1.71	2.25
		(4.12%)	(5.73%)	(0.18%)	(6.03%)	(7.96%)	(75.97%)	(100%)
600	120	0.08	0.12	0.003	0.12	0.14	1.71	2.16
		(3.54%)	(5.11%)	(0.16%)	(5.34%)	(6.53%)	(79.32%)	(100%)

[a] Plant cost includes cost of investment and operating and maintenance. The values in parentheses are percentage of total cost/gallon of ethanol production. Values may not sum to 100% due to rounding error. *Estimates are based on a 100 million gal/year biorefinery.

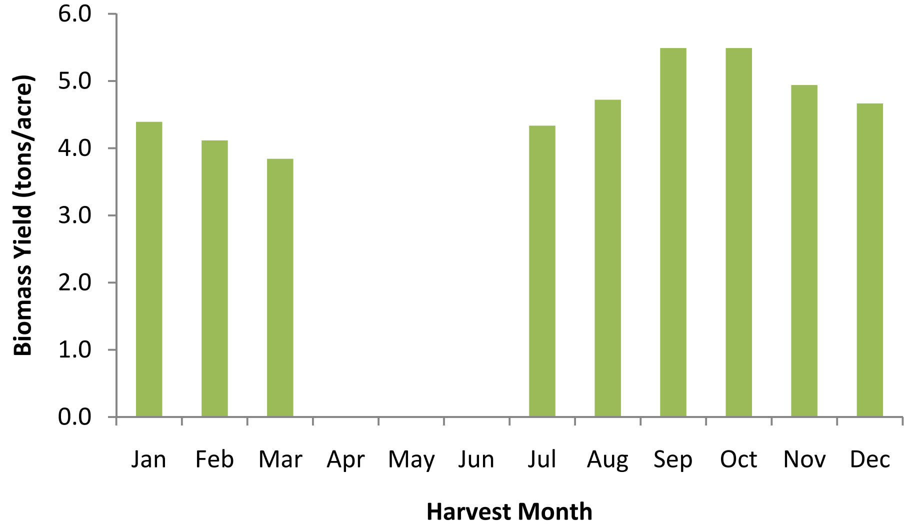
Table III-6: Estimated Breakeven Price of Ethanol ($ per gallon), Equivalent Wholesale Gasoline Price ($ per gallon) and the Price of Crude Oil ($ per barrel)

Investment Cost (millions $)	Conversion Rate (gallons of ethanol per dry ton)	Breakeven Price of Ethanol ($ per gallon)	Wholesale Gasoline Price[a] ($ per gallon)	Crude Oil Price[b] ($ per barrel)
	60	2.04	3.10	117.90
	80	1.77	2.69	102.00
200	100	1.61	2.45	92.50
	120	1.52	2.31	87.20
	60	2.36	3.59	136.50
	80	2.09	3.18	121.00
400	100	1.93	2.93	111.20
	120	1.84	2.80	106.00
	60	2.67	4.06	155.00
	80	2.41	3.66	139.50
600	100	2.25	3.42	130.00
	120	2.16	3.28	124.80

[a]Ethanol contains less energy (75,700 Btu) per gallon than unleaded gasoline (115,000 Btu). By this measure, the estimated $2.04 breakeven ethanol price would be equivalent to a wholesale price of $3.10 per gallon for unleaded gasoline.

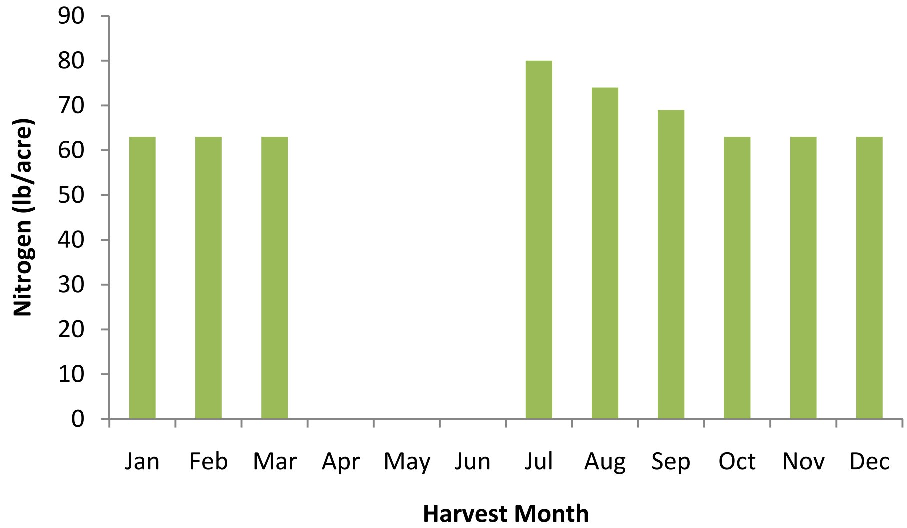
[b]To measure the relationship of the price of gasoline relative to crude oil prices a regression equation: wholesale gasoline ($ per gallon) = 0.05 + 0.0259 x crude oil price ($ per barrel) was estimated using 21 years data from U.S. Energy Information Administration, 2010a. By that measure, we found that for a crude oil price of $117.90 per barrel, the expected wholesale price of gasoline is $3.10 per gallon.

Note: Estimates are based on a 100 million gallon per year biorefinery.



Source: Annual switchgrass biomass yield from July to October are from field trail (Taliaferro 2007) and November to March are from Tembo (2000).

Figure III-1. Annual switchgrass biomass yield when harvested once per year by harvest month for counties with an expected base yield of 5.5 dry tons per acre per year.



Source: Annual nitrogen fertilizer requirements of July to October are from field trail (Taliaferro 2007) and November to March are from expert's opinion (Wu 2009; Kakani 2009).

Figure III-2. Annual nitrogen fertilizer required to achieve the plateau level of switchgrass yield when harvested once per year by harvest month.

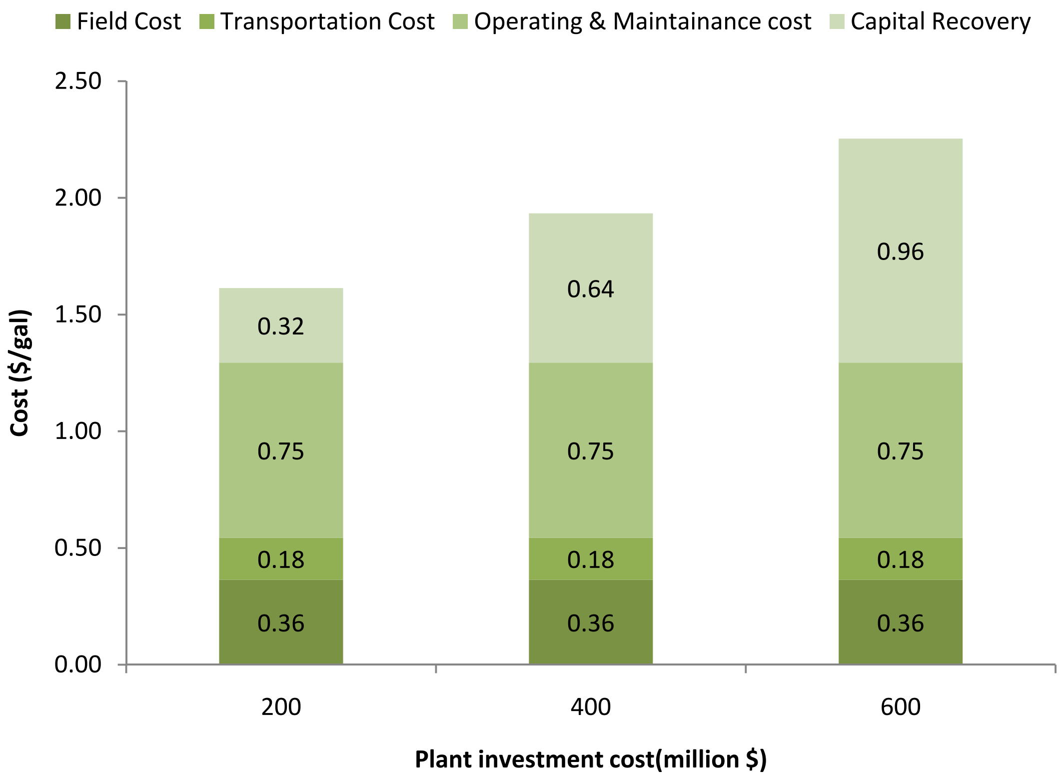


Figure III-3. Cost components and proportion are included at the breakeven ethanol price of $1.61, $1.93, and $2.25 per gallon with capital requirement of $200, $400, $600 million respectively for a conversion rate of 100 gallon per ton.

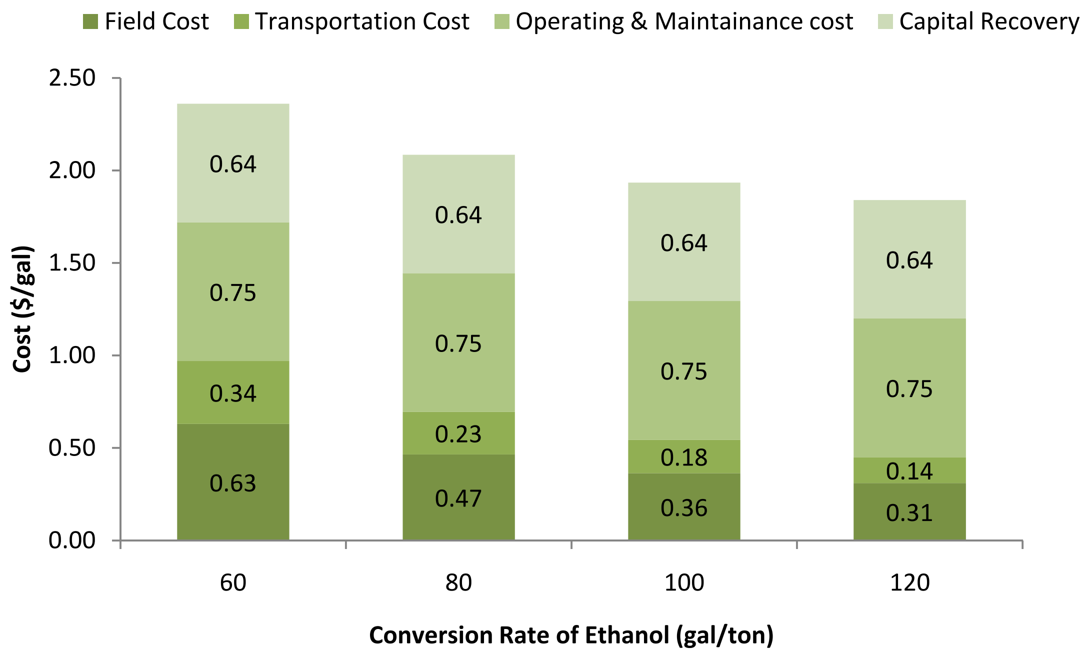


Figure III-4. Cost components and proportion are included at the breakeven ethanol price of $2.36, $2.09, $1.93 and $1.84 per gallon for conversion rates of 60, 80, 100 and 120 gallon per ton respectively with capital requirement of $400 million.

APPENDIX B for CHAPTER III -- GAMS/CPLEX Code for the Base Model

```
$OFFUPPER OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF
OPTIONS LIMROW=0, LIMCOL=0;
OPTION OPTCR = 0.0000;
OPTION SOLPRINT=OFF;
OPTION RESLIM=1000000;
OPTION ITERLIM=5000000;

SETS
 C Counties
   /Adair, Alfalfa, Atoka, Beaver, Beckham, Blaine, Bryan,Caddo,
Canadian, Carter, Cherokee, Choctaw, Cimarron, Clevelan, Coal,
Comanche, Cotton, Craig, Creek, Custer, Delaware, Dewey, Ellis,
Garfield, Garvin, Grady, Grant, Greer, Harmon, Harper, Haskell,Hughes,
Jackson, Jeffers, Johnston, Kay, Kingfish, Kiowa,Latimer, LeFlore,
Lincoln, Logan, Love, Major, Marshall, Mayes, McClain, McCurt,
McIntosh, Murray, Muskogee, Noble, Nowata, Okfuskee,Oklahoma, Okmulgee,
Osage, Ottawa, Pawnee, Payne, Pittsbur, Pontotoc, Pottawat, Pushmat,
RogerMil, Rogers, Seminole, Sequoyah,Stephens, Texas, Tillman, Tulsa,
Wagoner, Washing,
    Washita, Woods, Woodward/

 I(C) Biomass supplying counties
   /Adair, Alfalfa, Atoka, Beaver, Beckham, Blaine, Bryan, Caddo,
Canadian, Carter, Cherokee, Choctaw, Cimarron, Clevelan, Coal,
Comanche, Cotton, Craig, Creek, Custer, Delaware, Dewey, Ellis,
Garfield, Garvin, Grady, Grant, Greer, Harmon, Harper, Haskell,Hughes,
Jackson, Jeffers, Johnston, Kay, Kingfish, Kiowa,Latimer, LeFlore,
Lincoln, Logan, Love, Major, Marshall, Mayes, McClain, McCurt,
McIntosh, Murray, Muskogee, Noble, Nowata, Okfuskee, Oklahoma,
Okmulgee, Osage, Ottawa, Pawnee, Payne, Pittsbur, Pontotoc, Pottawat,
Pushmat,RogerMil, Rogers, Seminole, Sequoyah, Stephens, Texas,Tillman,
Tulsa, Wagoner, Washing, Washita, Woods, Woodward/

J(C) Processing plant locations
   /Pontotoc, Washing, Canadian, Garfield, Okmulgee, Payne/

R Geographical Regions of Oklahoma
```

```
/PANHAND,WCENTR, SWEST,NCENTR,CENTR,SCENTR,NEAST,ECENTR,SEAST/

 IR(I,R) Counties by geographical region
   /(Beaver, Cimarron, Texas, Harper, Ellis).PANHAND, (Dewey, Blaine,
RogerMil, Custer, Beckham, Washita).WCENTR, (Caddo, Kiowa, Greer,
Harmon, Jackson, Comanche, Tillman, Cotton).SWEST, (Woods, Woodward,
Alfalfa, Major, Grant, Garfield, Kay, Noble).NCENTR,(Kingfish, Logan,
Payne, Canadian, Oklahoma, Lincoln, Creek, Okfuskee, Grady, McClain,
Clevelan, Pottawat, Seminole).CENTR, (Garvin, Pontotoc, Stephens,
Jeffers, Love, Marshall, Bryan, Atoka, Coal, Murray, Carter,
Johnston).SCENTR, (Pawnee, Osage, Washing, Tulsa, Nowata, Rogers,
Wagoner, Craig, Mayes, Ottawa, Delaware).NEAST, (Cherokee, Adair,
Sequoyah, Okmulgee, Muskogee, McIntosh, Hughes, Pittsbur,
Haskell).ECENTR, (LeFlore, Choctaw, McCurt, Latimer,Pushmat).SEAST/

 JR(J,R) Prospective plant locations by region
   /Pontotoc.SCENTR, Washing.NEAST, Okmulgee.ECENTR, (Canadian,Payne).
CENTR, (Garfield). NCENTR/

 K Lignocellulosic feedstocks
   /Switchgr, Switchpa/

 CRS(K) "Crop residues and switchgrass"
   /Switchgr/

 KF Lignocellulosic biomass differentiated by fertility program
   /Switchg, switchpa50/

 KKF(K,KF) Allocating fertility subactivities to biomass activities
   /Switchgr.Switchg, Switchpa.switchpa50/

 CA Feedstock Categories
   /CR, NP, IP, SG/

 KCA(K,CA) Mapping lignocellulosic feedstocks to feedstock categories
  /Switchgr.SG, Switchpa.IP/

L Categories of land
   /Cropland, Cropast /

LC(L) Crop land
   /Cropland, Cropast /

LK(L,K) Mapping biomass types to suitable land in which they can be
grown

   /(Cropland, Cropast).(Switchgr,Switchpa)/

BC Biomass production cost categories
   /Estcost, Maincost, Landrent, Biopcost/
```

```
BCO(BC) Biomass opportunity cost categories
   /Landrent, Biopcost/

 G Products and by-products of the process
   /Ethanol, CO2, N2, Ash/

 E(G) Ethanol only
   /Ethanol/

 B(G) Process by-products
   /CO2, N2, Ash/

 S Plant Size
   /Small, Medium, Large/

 FT Facility type at the plant location
  /Storage, Process/

M Months of the production year
   /Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb, Mar/

 M1(M) The first month of the production year
   /Apr/

M2(M) Months after the first month
   /May, Jun, Jul, Aug, Sep, Oct, Nov, Dec, Jan, Feb, Mar/

SCALAR BIPROP Proportion of biomass acres available for biorefinery
/0.10/;

SCALAR BIPROP1 Proportion of biomass acres available for biorefinery
/0.10/;

SCALAR DR "Discount rate" /0.15/;

SCALAR T "Project life in years" /20/;

SCALAR
  IOE Transformation rate in gallons of ethanol per ton of biomass
/100/
  IOC Transformation rate in tons of CO2 per ton of biomass /0/
  ION Transformation rate in tons of N per ton of biomass /0/
  IOA Trans rate in tons of ash and other byproducts per ton of biomass
/0/;

PARAMETER LAMBDA(K,G) Input-output coefficients;
  LAMBDA(K,G)$(ORD(G) EQ 1) = IOE;
  LAMBDA(K,G)$(ORD(G) EQ 2) = IOC;
  LAMBDA(K,G)$(ORD(G) EQ 3) = ION;
  LAMBDA(K,G)$(ORD(G) EQ 4) = IOA;
```

```
SCALAR TRKLOAD Truck capacity in tons of biomass /16.01/;

SCALAR CAPADJ "Capacity scaling/adjustment factor" /0.5/;

SCALAR COADJ  "Construction cost scaling/adjustment factor"
/1.4545454545455/;

PARAMETER CAP50(FT) "Processing/storage capacity for 50 m gal plant"  ;
     CAP50("STORAGE")= 3000000/IOE;
     CAP50("PROCESS")= 50000000 ;

PARAMETER CAP(S,FT) Storage and processing capacity by plant size;
   CAP(S,FT)$(ORD(S) EQ 2) = CAP50(FT);
   CAP(S,FT)$(ORD(S) EQ 1) = CAP50(FT)*CAPADJ;
   CAP(S,FT)$(ORD(S) EQ 3) = CAP50(FT)/CAPADJ;

PARAMETER CAPP(S) "Facility monthly capacity in gallons";
   CAPP(S) = CAP(S,"PROCESS")/12;

PARAMETER FC42(FT) "Construction costs for 50 m gallon plant in $"
   /STORAGE   0
    PROCESS 275000000 /;

PARAMETER FC(S,FT) Construction and facility costs by plant size;
   FC(S,FT)$(ORD(S) EQ 2) = FC42(FT);
   FC(S,FT)$(ORD(S) EQ 1) = FC42(FT)/COADJ;
   FC(S,FT)$(ORD(S) EQ 3) = FC42(FT)*COADJ;

SCALAR AOM "For O & M Cost factor-$ gallon capacity" /0.75/;

PARAMETER OMAP(S,FT) "Total Annual O & M costs in $ by Plant size by
facility" ;

    OMAP(S,"STORAGE")=  0.00;
    OMAP("Small","PROCESS")=   AOM*25000000;
    OMAP("Medium","PROCESS")=  AOM*50000000;
    OMAP("Large","PROCESS")=   AOM*100000000;

TABLE FSV(S,FT) "Facility salvage value in $ by plant size"
             Storage     Process
  Small         0           0
  Medium        0           0
  Large         0           0      ;

PARAMETER AFC(S,FT) Facility annual fixed charge by plant size;
 AFC(S,FT)=[FC(S,FT)-FSV(S,FT)];

PARAMETER PVAF Present value of an annuity factor;
PVAF= [POWER{(1+DR),T}-1]/[DR*POWER{(1+DR),T}];
```

```
PARAMETER RHO(G) "Output price vector in $ per unit"
  /Ethanol  1.93
   CO2      -24.70
   N2      -246.40
   Ash       -0.02/;

SCALAR PN "Price of nitrogen in $ per lb" /0.46/;

TABLE NIT(KF,M) Level of nitrogen by fertility program in lb per acre
by month
           Apr May Jun  Jul Aug  Sep Oct Nov  Dec  Jan  Feb  Mar
Switchg    0    0   0   80  74   69   63  63   63   63   63  63
switchpa50 0    0   0   80  74   69   63  63   63   63   63  63  ;

PARAMETER NCOST(KF, M) Cost of applied nitrogen in USD per acre;
   NCOST(KF, M) = NIT(KF,M)*PN;

SCALAR PP "Price of Phosphorus (P2O5) in $ per lb" /0.53/;

TABLE PIT(KF,M) Level of phosphorus by fertility program in lb per acre
by month

           Apr May Jun  Jul Aug  Sep Oct Nov Dec Jan Feb Mar
Switchg    0    0   0   10  10   10   0  0   0   0   0   0
switchpa50 0    0   0   10  10   10   0  0   0   0   0   0  ;

PARAMETER PCOST(KF, M) Cost of applied phosphorus in USD per acre;
   PCOST(KF,M) = PIT(KF,M)*PP;

TABLE YAD(K,M) Proportion of potential yield by harvest month
         Apr  May  Jun  Jul   Aug   Sep   Oct   Nov   Dec   Jan   Feb
Mar
Switchgr  0    0    0   0.79  0.86  1.00  1.00  0.90  0.85  0.80  0.75
0.70
switchpa  0    0    0   0.79  0.86  1.00  1.00  0.90  0.85  0.80  0.75
0.70 ;

PARAMETER THETAI(K) Usable proportion of stored biomass at the source
/Switchgr  0.99
 switchpa  0.99 /;

PARAMETER THETAJ(K) Usable proportion of stored biomass at the plant
/  Switchgr  0.99
   switchpa  0.99 /;

PARAMETER GAMMA(K) Biomass storage cost at source in USD per ton
(Huhnke)
/ Switchgr  2.00
  switchpa  2.00  /;
```

```
PARAMETER PSI(K) Biomass purchase cost in USD per ton
/ Switchgr  0.00
  switchpa  0.00  /;

TABLE POC(K,BC) "Biomass production and opportunity costs in $ per
acre"
               Estcost   Maincost   Landrent   Biopcost
  Switchgr     27.86       4.14      60.00         0
  Switchpa     25.02       4.14      40.00         0    ;

PARAMETER TPOC(K) "Total production/procurement cost of feedstocks in
$/acre";

TPOC(K) = SUM(BC, POC(K,BC));

TABLE POTACRES(I,L) Potential acres by land category
          Cropland        Cropast
Adair        46324          44763
Alfalfa     271955          49956
Atoka        57748          98813
Beaver      310308          84939
Beckham     157723          80958
Blaine      219363          84047
Bryan        97369         100578
Caddo       260929         124486
Canadian    214127          93425
Carter       45923         103869
Cherokee     43416          48556
Choctaw      60391          66705
Cimarron    388657          80389
Clevelan     40745          36992
Coal         35403          53581
Comanche    106891          71247
Cotton      118662          76423
Craig       100880          53265
Creek        63439          67638
Custer      206020          78109
Delaware     68807          55246
Dewey       144416          60071
Ellis       126125          56664
Garfield    370406          77310
Garvin       90184          90066
Grady       166458         100136
Grant       390519          46510
Greer       127020          48223
Harmon      109729          47969
Harper      152270          52350
Haskell      53092          55335
Hughes       54102          70900
```

```
Jackson     257345          51705
Jeffers      46183          81025
Johnston     36826          59455
Kay         282574          41131
Kingfish    259205         112701
Kiowa       261360          79483
Latimer      26694          33420
LeFlore     100105          84559
Lincoln      88540         105343
Logan       102716          75870
Love         42413          51625
Major       181718          72804
Marshall     22672          22983
Mayes        94805          56552
McClain      70625          62646
McCurt       72282          73571
McIntosh     54492          51654
Murray       24577          29328
Muskogee    110552          60671
Noble       162132          43876
Nowata       53785          41539
Okfuskee     39840          56325
Oklahoma     55254          29413
Okmulgee     64530          49171
Osage        79304          90619
Ottawa       94520          30432
Pawnee       45139          35435
Payne        66127          70184
Pittsbur     72631          87358
Pontotoc     56046          86426
Pottawat     77077          68016
Pushmat      34526          52986
RogerMil     87505          94081
Rogers       78678          53688
Sequoyah     58952          43994
Seminole     48128          69024
Stephens     60311          99913
Texas       524360          51130
Tillman     262696          69512
Tulsa        51560          29209
Wagoner     102480          29119
Washing      51866          23505
Washita     266911          93825
Woods       246998          68737
Woodward    128111          77695
;

TABLE BIOYLD1(I,KF) Biomass yield in lbs per acre
          Switchg    Switchpa50
Adair      13000      13000
```

Alfalfa	10000	10000
Atoka	13000	13000
Beaver	0	0
Beckham	0	0
Blaine	10000	10000
Bryan	12000	12000
Caddo	12000	12000
Canadian	10000	10000
Carter	12000	12000
Cherokee	13000	13000
Choctaw	12000	12000
Cimarron	0	0
Clevelan	10000	10000
Coal	12000	12000
Comanche	0	0
Cotton	0	0
Craig	12000	12000
Creek	12000	12000
Custer	0	0
Delaware	13000	13000
Dewey	0	0
Ellis	0	0
Garfield	10000	10000
Garvin	10000	10000
Grady	10000	10000
Grant	10000	10000
Greer	0	0
Harmon	0	0
Harper	0	0
Haskell	13000	13000
Hughes	13000	13000
Jackson	0	0
Jeffers	10000	10000
Johnston	12000	12000
Kay	10000	10000
Kingfish	10000	10000
Kiowa	0	0
Latimer	13000	13000
LeFlore	13000	13000
Lincoln	12000	12000
Logan	10000	10000
Love	12000	12000
Major	0	0
Marshall	12000	12000
Mayes	12000	12000
McClain	10000	10000
McCurt	13000	13000
McIntosh	13000	13000
Murray	12000	12000

```
Muskogee   12000      12000
Noble      10000      10000
Nowata     12000      12000
Okfuskee   12000      12000
Oklahoma   12000      12000
Okmulgee   12000      12000
Osage      12000      12000
Ottawa     12000      12000
Pawnee     10000      10000
Payne      10000      10000
Pittsbur   13000      13000
Pontotoc   12000      12000
Pottawat   10000      10000
Pushmat    13000      13000
RogerMil     0          0
Rogers     12000      12000
Seminole   12000      12000
Sequoyah   13000      13000
Stephens   12000      12000
Texas        0          0
Tillman      0          0
Tulsa      12000      12000
Wagoner    12000      12000
Washing    12000      12000
Washita      0          0
Woods        0          0
Woodward     0          0   ;

TABLE DELTA(I,J) Miles from biomass source i to facility location j
         Pontotoc  Washing Canadian  Garfield
Adair       199      161      240      239
Alfalfa     248      177      143       83
Atoka        80      210      189      245
Beaver      352      323      243      216
Beckham     230      310      138      190
Blaine      185      221       76       98
Bryan        96      262      205      261
Caddo       142      251       91      153
Canadian    144      206       33       95
Carter       95      256      157      213
Cherokee    180      136      215      213
Choctaw     132      241      241      297
Cimarron    460      444      351      324
Clevelan     93      195       74      130
Coal         58      198       99      223
Comanche    148      271      115      177
Cotton      143      282      127      189
Craig       209       79      218      208
Creek       118      109      127      146
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Custer	208	265	99	142
Delaware	230	116	239	229
Dewey	232	244	123	115
Ellis	278	290	169	160
Garfield	200	165	95	33
Garvin	66	221	116	171
Grady	121	230	74	135
Grant	223	145	128	66
Greer	218	323	154	206
Harmon	236	352	186	238
Harper	293	254	184	156
Haskell	74	161	201	235
Hughes	66	162	131	186
Jackson	205	321	162	214
Jeffers	137	283	128	190
Johnston	66	230	169	225
Kay	200	122	155	94
Kingfish	158	190	54	68
Kiowa	195	301	132	184
Latimer	110	156	206	230
LeFlore	179	216	262	290
Lincoln	106	139	98	134
Logan	141	161	84	93
Love	103	264	165	221
Major	223	208	114	78
Marshall	75	239	169	225
Mayes	183	90	192	181
McClain	77	212	91	147
McCurt	184	293	294	349
McIntosh	135	141	176	213
Murray	63	224	144	200
Muskogee	156	125	191	199
Noble	162	133	116	72
Nowata	193	45	202	177
Okfuskee	95	141	130	178
Oklahoma	113	180	56	112
Okmulgee	114	108	155	174
Osage	196	75	205	155
Ottawa	227	98	236	226
Pawnee	153	110	149	101
Payne	137	129	117	97
Pittsbur	100	176	187	241
Pontotoc	29	193	140	196
Pottawat	81	168	96	152
Pushmat	112	195	244	268
RogerMil	256	309	151	185
Rogers	174	80	183	173
Seminole	70	162	128	183
Sequoyah	178	172	219	246

Stephens	120	262	106	168
Texas	398	383	289	261
Tillman	188	311	155	217
Tulsa	146	76	155	146
Wagoner	165	111	191	184
Washing	193	29	202	161
Washita	194	279	110	162
Woods	284	212	175	119
Woodward	256	246	147	120

+	Okmulgee	Payne
Adair	125	185
Alfalfa	232	148
Atoka	127	185
Beaver	362	271
Beckham	267	217
Blaine	197	124
Bryan	157	201
Caddo	198	165
Canadian	164	119
Carter	183	180
Cherokee	100	160
Choctaw	158	236
Cimarron	470	380
Clevelan	138	109
Coal	115	163
Comanche	218	184
Cotton	229	196
Craig	128	155
Creek	67	86
Custer	228	169
Delaware	150	176
Dewey	243	152
Ellis	288	197
Garfield	183	99
Garvin	155	143
Grady	177	144
Grant	202	118
Greer	274	234
Harmon	299	265
Harper	303	212
Haskell	94	181
Hughes	88	126
Jackson	268	235
Jeffers	225	197
Johnston	156	171
Kay	179	95
Kingfish	166	94
Kiowa	251	211
Latimer	96	188

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LeFlore    154      237
Lincoln     98       70
Logan      137       65
Love       192      189
Major      220      130
Marshall   165      176
Mayes      102      128
McClain    147      126
McCurt     211      289
McIntosh    66      155
Murray     151      148
Muskogee    76      145
Noble      144       56
Nowata     112      137
Okfuskee    65      117
Oklahoma   133       94
Okmulgee    24      115
Osage      143      125
Ottawa     146      172
Pawnee     124       64
Payne      122       31
Pittsbur    93      182
Pontotoc   119      135
Pottawat   105       91
Pushmat    135      226
RogerMil   280      213
Rogers      93      120
Seminole    91      123
Sequoyah   112      192
Stephens   209      175
Texas      408      317
Tillman    258      224
Tulsa       67       93
Wagoner     84      131
Washing    113      127
Washita    232      189
Woods      268      184
Woodward   266      176    ;

PARAMETER BYLD(I,KF) Biomass yield in tons per acre;
  BYLD(I,KF) = BIOYLD1(I,KF)/2000;

PARAMETER TRCA(I,J)  "Biomass transportation cost in $ per 16.01 dry
ton truck";

TRCA(I,J) = 12.78 + 1.72*2*DELTA(I,J);
PARAMETER TAU(I,J)  "Biomass transportation cost in $ per ton";
  TAU(I,J) = TRCA(I,J)/TRKLOAD;
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TABLE FWD(I,M) Field-Workdays for Mowing Available in Oklahoma by county and month

	Apr	May	Jun	Jul	Aug	Sep	Oct
Adair	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Alfalfa	15.00	17.00	16.00	17.00	18.00	20.00	17.00
Atoka	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Beaver	16.00	15.00	15.00	17.00	15.00	19.00	16.00
Beckham	17.00	15.00	14.00	19.00	15.00	16.00	17.00
Blaine	17.00	15.00	14.00	19.00	15.00	16.00	17.00
Bryan	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Caddo	15.00	15.00	11.00	20.00	15.00	15.00	15.00
Canadian	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Carter	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Cherokee	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Choctaw	11.00	16.00	12.00	18.00	18.00	18.00	14.00
Cimarron	16.00	15.00	15.00	17.00	15.00	19.00	16.00
Clevelan	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Coal	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Comanche	15.00	15.00	11.00	20.00	15.00	15.00	15.00
Cotton	15.00	15.00	11.00	20.00	15.00	15.00	15.00
Craig	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Creek	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Custer	17.00	15.00	14.00	19.00	15.00	16.00	17.00
Delaware	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Dewey	17.00	15.00	14.00	19.00	15.00	16.00	17.00
Ellis	16.00	15.00	15.00	17.00	15.00	19.00	16.00
Garfield	15.00	17.00	16.00	17.00	18.00	20.00	17.00
Garvin	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Grady	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Grant	15.00	17.00	16.00	17.00	18.00	20.00	17.00
Greer	15.00	15.00	11.00	20.00	15.00	15.00	15.00
Harmon	15.00	15.00	11.00	20.00	15.00	15.00	15.00
Harper	16.00	15.00	15.00	17.00	15.00	19.00	16.00
Haskell	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Hughes	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Jackson	15.00	15.00	11.00	20.00	15.00	15.00	15.00
Jeffers	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Johnston	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Kay	15.00	17.00	16.00	17.00	18.00	20.00	17.00
Kingfish	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Kiowa	15.00	15.00	11.00	20.00	15.00	15.00	15.00
Latimer	11.00	16.00	12.00	18.00	18.00	18.00	14.00
LeFlore	11.00	16.00	12.00	18.00	18.00	14.00	14.00
Lincoln	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Logan	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Love	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Major	15.00	17.00	16.00	17.00	18.00	20.00	17.00
Marshall	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Mayes	16.00	16.00	11.00	16.00	20.00	17.00	16.00

McClain	17.00	16.00	14.00	19.00	17.00	18.00	16.00
McCurt	11.00	16.00	12.00	18.00	18.00	18.00	14.00
McIntosh	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Murray	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Muskogee	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Noble	15.00	17.00	16.00	17.00	18.00	20.00	17.00
Nowata	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Okfuskee	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Oklahoma	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Okmulgee	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Osage	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Ottawa	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Pawnee	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Payne	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Pittsbur	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Pontotoc	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Pottawat	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Pushmat	11.00	16.00	12.00	18.00	18.00	18.00	14.00
RogerMil	17.00	15.00	14.00	19.00	15.00	16.00	17.00
Rogers	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Seminole	17.00	16.00	14.00	19.00	17.00	18.00	16.00
Sequoyah	16.00	15.00	16.00	20.00	19.00	17.00	17.00
Stephens	14.00	14.00	15.00	17.00	19.00	16.00	13.00
Texas	16.00	15.00	17.00	15.00	19.00	16.00	16.00
Tillman	15.00	15.00	11.00	20.00	15.00	15.00	15.00
Tulsa	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Wagoner	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Washing	16.00	16.00	11.00	16.00	20.00	17.00	16.00
Washita	17.00	15.00	14.00	19.00	15.00	16.00	17.00
Woods	15.00	17.00	16.00	17.00	18.00	20.00	17.00
Woodward	15.00	17.00	16.00	17.00	18.00	20.00	17.00

+	Nov	Dec	Jan	Feb	Mar
Adair	9.00	15.00	17.00	10.00	18.00
Alfalfa	14.00	15.00	18.00	18.00	16.00
Atoka	13.00	16.00	13.00	9.00	18.00
Beaver	10.00	21.00	21.00	15.00	17.00
Beckham	12.00	19.00	18.00	17.00	18.00
Blaine	12.00	19.00	18.00	17.00	18.00
Bryan	13.00	16.00	13.00	9.00	18.00
Caddo	14.00	19.00	16.00	16.00	19.00
Canadian	11.00	18.00	19.00	18.00	16.00
Carter	13.00	16.00	13.00	9.00	18.00
Cherokee	9.00	15.00	17.00	10.00	18.00
Choctaw	13.00	12.00	15.00	12.00	15.00
Cimarron	10.00	21.00	21.00	15.00	17.00
Clevelan	11.00	18.00	19.00	18.00	16.00
Coal	13.00	16.00	13.00	9.00	18.00
Comanche	14.00	19.00	16.00	16.00	19.00
Cotton	14.00	19.00	16.00	16.00	19.00

Craig	14.00	18.00	16.00	16.00	12.00
Creek	11.00	18.00	19.00	18.00	16.00
Custer	12.00	19.00	18.00	17.00	18.00
Delaware	14.00	18.00	16.00	16.00	12.00
Dewey	12.00	19.00	18.00	17.00	18.00
Ellis	10.00	21.00	21.00	15.00	17.00
Garfield	14.00	15.00	18.00	18.00	16.00
Garvin	13.00	16.00	13.00	9.00	18.00
Grady	11.00	18.00	19.00	18.00	16.00
Grant	14.00	15.00	18.00	18.00	16.00
Greer	14.00	19.00	16.00	16.00	19.00
Harmon	14.00	19.00	16.00	16.00	19.00
Harper	10.00	21.00	21.00	15.00	17.00
Haskell	9.00	15.00	17.00	10.00	18.00
Hughes	9.00	15.00	17.00	10.00	18.00
Jackson	14.00	19.00	16.00	16.00	19.00
Jeffers	13.00	16.00	13.00	9.00	18.00
Johnston	13.00	16.00	13.00	9.00	18.00
Kay	14.00	15.00	18.00	18.00	16.00
Kingfish	11.00	18.00	19.00	18.00	16.00
Kiowa	14.00	19.00	16.00	16.00	19.00
Latimer	13.00	12.00	15.00	12.00	15.00
LeFlore	13.00	12.00	15.00	12.00	15.00
Lincoln	11.00	18.00	19.00	18.00	16.00
Logan	11.00	18.00	19.00	18.00	16.00
Love	13.00	16.00	13.00	9.00	18.00
Major	14.00	15.00	18.00	18.00	16.00
Marshall	13.00	16.00	13.00	9.00	18.00
Mayes	14.00	18.00	16.00	16.00	12.00
McClain	11.00	18.00	19.00	18.00	16.00
McCurt	13.00	12.00	15.00	12.00	15.00
McIntosh	9.00	15.00	17.00	10.00	18.00
Murray	13.00	16.00	13.00	9.00	18.00
Muskogee	9.00	15.00	17.00	10.00	18.00
Noble	14.00	15.00	18.00	18.00	16.00
Nowata	14.00	18.00	16.00	16.00	12.00
Okfuskee	11.00	18.00	19.00	18.00	16.00
Oklahoma	11.00	18.00	19.00	18.00	16.00
Okmulgee	9.00	15.00	17.00	10.00	18.00
Osage	14.00	18.00	16.00	16.00	12.00
Ottawa	14.00	18.00	16.00	16.00	12.00
Pawnee	14.00	18.00	16.00	16.00	12.00
Payne	11.00	18.00	19.00	18.00	16.00
Pittsbur	9.00	15.00	17.00	10.00	18.00
Pontotoc	13.00	16.00	13.00	9.00	18.00
Pottawat	11.00	18.00	19.00	18.00	16.00
Pushmat	13.00	12.00	15.00	12.00	15.00
RogerMil	12.00	19.00	18.00	17.00	18.00
Rogers	14.00	18.00	16.00	16.00	12.00

Seminole	11.00	18.00	19.00	18.00	16.00
Sequoyah	9.00	15.00	17.00	10.00	18.00
Stephens	13.00	16.00	13.00	9.00	18.00
Texas	10.00	21.00	21.00	15.00	17.00
Tillman	14.00	19.00	16.00	16.00	19.00
Tulsa	14.00	18.00	16.00	16.00	12.00
Wagoner	14.00	18.00	16.00	16.00	12.00
Washing	14.00	18.00	16.00	16.00	12.00
Washita	12.00	19.00	18.00	17.00	18.00
Woods	14.00	15.00	18.00	18.00	16.00
Woodward	14.00	15.00	18.00	18.00	16.00

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TABLE BWD(I,M) Field Workdays for Baling Available in Oklahoma by county and month

	Apr	May	Jun	Jul	Aug	Sep	Oct
Adair	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Alfalfa	11.00	11.00	13.00	16.00	14.00	13.00	7.00
Atoka	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Beaver	9.00	8.00	11.00	15.00	14.00	11.00	11.00
Beckham	11.00	10.00	8.00	16.00	12.00	8.00	3.00
Blaine	11.00	10.00	8.00	16.00	12.00	8.00	3.00
Bryan	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Caddo	10.00	9.00	8.00	15.00	9.00	8.00	5.00
Canadian	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Carter	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Cherokee	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Choctaw	5.00	8.00	4.00	16.00	13.00	11.00	2.00
Cimarron	9.00	8.00	11.00	15.00	14.00	11.00	11.00
Clevelan	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Coal	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Comanche	10.00	9.00	8.00	15.00	9.00	8.00	5.00
Cotton	10.00	9.00	8.00	15.00	9.00	8.00	5.00
Craig	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Creek	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Custer	11.00	10.00	8.00	16.00	12.00	8.00	3.00
Delaware	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Dewey	11.00	10.00	8.00	16.00	12.00	8.00	3.00
Ellis	9.00	8.00	11.00	15.00	14.00	11.00	11.00
Garfield	11.00	11.00	13.00	16.00	14.00	13.00	7.00
Garvin	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Grady	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Grant	11.00	11.00	13.00	16.00	14.00	13.00	7.00
Greer	10.00	9.00	8.00	15.00	9.00	8.00	5.00
Harmon	10.00	9.00	8.00	15.00	9.00	8.00	5.00
Harper	9.00	8.00	11.00	15.00	14.00	11.00	11.00
Haskell	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Hughes	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Jackson	10.00	9.00	8.00	15.00	9.00	8.00	5.00

Jeffers	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Johnston	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Kay	11.00	11.00	13.00	16.00	14.00	13.00	7.00
Kingfish	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Kiowa	10.00	9.00	8.00	15.00	9.00	8.00	5.00
Latimer	5.00	8.00	4.00	16.00	13.00	11.00	2.00
LeFlore	5.00	8.00	4.00	16.00	13.00	11.00	2.00
Lincoln	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Logan	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Love	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Major	11.00	11.00	13.00	16.00	14.00	13.00	7.00
Marshall	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Mayes	8.00	10.00	8.00	13.00	12.00	9.00	6.00
McClain	10.00	10.00	10.00	16.00	14.00	12.00	5.00
McCurt	5.00	8.00	4.00	16.00	13.00	11.00	2.00
McIntosh	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Murray	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Muskogee	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Noble	11.00	11.00	13.00	16.00	14.00	13.00	7.00
Nowata	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Okfuskee	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Oklahoma	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Okmulgee	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Osage	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Ottawa	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Pawnee	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Payne	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Pittsbur	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Pontotoc	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Pottawat	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Pushmat	5.00	8.00	4.00	16.00	13.00	11.00	2.00
RogerMil	11.00	10.00	8.00	16.00	12.00	8.00	3.00
Rogers	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Seminole	10.00	10.00	10.00	16.00	14.00	12.00	5.00
Sequoyah	9.00	9.00	10.00	16.00	15.00	9.00	6.00
Stephens	8.00	9.00	11.00	15.00	14.00	12.00	5.00
Texas	9.00	8.00	11.00	15.00	14.00	11.00	11.00
Tillman	10.00	9.00	8.00	15.00	9.00	8.00	5.00
Tulsa	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Wagoner	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Washing	8.00	10.00	8.00	13.00	12.00	9.00	6.00
Washita	11.00	10.00	8.00	16.00	12.00	8.00	3.00
Woods	11.00	11.00	13.00	16.00	14.00	13.00	7.00
Woodward	11.00	11.00	13.00	16.00	14.00	13.00	7.00

+	Nov	Dec	Jan	Feb	Mar
Adair	8.00	15.00	15.00	8.00	17.00
Alfalfa	11.00	13.00	16.00	17.00	14.00
Atoka	12.00	16.00	12.00	9.00	17.00
Beaver	9.00	21.00	20.00	14.00	17.00

Beckham	12.00	18.00	18.00	17.00	18.00
Blaine	12.00	18.00	18.00	17.00	18.00
Bryan	12.00	16.00	12.00	9.00	17.00
Caddo	12.00	19.00	16.00	15.00	19.00
Canadian	11.00	17.00	18.00	17.00	16.00
Carter	12.00	16.00	12.00	9.00	17.00
Cherokee	8.00	15.00	15.00	8.00	17.00
Choctaw	10.00	10.00	11.00	10.00	15.00
Cimarron	9.00	21.00	20.00	14.00	17.00
Clevelan	11.00	17.00	18.00	17.00	16.00
Coal	12.00	16.00	12.00	9.00	17.00
Comanche	12.00	19.00	16.00	15.00	19.00
Cotton	12.00	19.00	16.00	15.00	19.00
Craig	12.00	15.00	15.00	15.00	12.00
Creek	11.00	17.00	18.00	17.00	16.00
Custer	12.00	18.00	18.00	17.00	18.00
Delaware	12.00	15.00	15.00	15.00	12.00
Dewey	12.00	18.00	18.00	17.00	18.00
Ellis	9.00	21.00	20.00	14.00	17.00
Garfield	11.00	13.00	16.00	17.00	14.00
Garvin	12.00	16.00	12.00	9.00	17.00
Grady	11.00	17.00	18.00	17.00	16.00
Grant	11.00	13.00	16.00	17.00	14.00
Greer	12.00	19.00	16.00	15.00	19.00
Harmon	12.00	19.00	16.00	15.00	19.00
Harper	9.00	21.00	20.00	14.00	17.00
Haskell	8.00	15.00	15.00	8.00	17.00
Hughes	8.00	15.00	15.00	8.00	17.00
Jackson	12.00	19.00	16.00	15.00	19.00
Jeffers	12.00	16.00	12.00	9.00	17.00
Johnston	12.00	16.00	12.00	9.00	17.00
Kay	11.00	13.00	16.00	17.00	14.00
Kingfish	11.00	17.00	18.00	17.00	16.00
Kiowa	12.00	19.00	16.00	15.00	19.00
Latimer	10.00	10.00	11.00	10.00	15.00
LeFlore	10.00	10.00	11.00	10.00	15.00
Lincoln	11.00	17.00	18.00	17.00	16.00
Logan	11.00	17.00	18.00	17.00	16.00
Love	12.00	16.00	12.00	9.00	17.00
Major	11.00	13.00	16.00	17.00	14.00
Marshall	12.00	16.00	12.00	9.00	17.00
Mayes	12.00	15.00	15.00	15.00	12.00
McClain	11.00	17.00	18.00	17.00	16.00
McCurt	10.00	10.00	11.00	10.00	15.00
McIntosh	8.00	15.00	15.00	8.00	17.00
Murray	12.00	16.00	12.00	9.00	17.00
Muskogee	8.00	15.00	15.00	8.00	17.00
Noble	11.00	13.00	16.00	17.00	14.00
Nowata	12.00	15.00	15.00	15.00	12.00

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Okfuskee         11.00   17.00   18.00   17.00   16.00
Oklahoma         11.00   17.00   18.00   17.00   16.00
Okmulgee          8.00   15.00   15.00    8.00   17.00
Osage            12.00   15.00   15.00   15.00   12.00
Ottawa           12.00   15.00   15.00   15.00   12.00
Pawnee           12.00   15.00   15.00   15.00   12.00
Payne            11.00   17.00   18.00   17.00   16.00
Pittsbur          8.00   15.00   15.00    8.00   17.00
Pontotoc         12.00   16.00   12.00    9.00   17.00
Pottawat         11.00   17.00   18.00   17.00   16.00
Pushmat          10.00   10.00   11.00   10.00   15.00
RogerMil         12.00   18.00   18.00   17.00   18.00
Rogers           12.00   15.00   15.00   15.00   12.00
Seminole         11.00   17.00   18.00   17.00   16.00
Sequoyah          8.00   15.00   15.00    8.00   17.00
Stephens         12.00   16.00   12.00    9.00   17.00
Texas             9.00   21.00   20.00   14.00   17.00
Tillman          12.00   19.00   16.00   15.00   19.00
Tulsa            12.00   15.00   15.00   15.00   12.00
Wagoner          12.00   15.00   15.00   15.00   12.00
Washing          12.00   15.00   15.00   15.00   12.00
Washita          12.00   18.00   18.00   17.00   18.00
Woods            11.00   13.00   16.00   17.00   14.00
Woodward         11.00   13.00   16.00   17.00   14.00
;

PARAMETERS DCAMHU(M)"Daily Capacity of a Mowing Harvest Unit in tons by
Month"
/Apr 341
 May 366
 Jun 375
 Jul 369
 Aug 348
 Sep 320
 Oct 292
 Nov 264
 Dec 251
 Jan 258
 Feb 282
 Mar 310/;

PARAMETERS DCABHU(M)"Daily Capacity of a Baling Harvest Unit in tons by
Month"
/Apr 454
 May 487
 Jun 500
 Jul 492
 Aug 463
 Sep 425
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 Oct 388
 Nov 351
 Dec 335
 Jan 343
 Feb 376
 Mar 413 /;

SCALAR OMEGAM "Cost of a Harvest Unit for Mowing in $ per Unit"
/106463/;

SCALAR OMEGAB "Cost of a Harvest Unit for Baling in $ per Unit"
/545516/;

PARAMETER CAPHUM(I,M) "Monthly capacity of harvest unit FOR MOWING in
tons";
        CAPHUM(I,M) = FWD(I,M)*DCAMHU(M);

PARAMETER CAPHUB(I,M) "Monthly capacity of harvest FOR BALING unit in
tons";
        CAPHUB(I,M) = BWD(I,M)*DCABHU(M);

VARIABLES
  NPW                Net present value for the ethanol production
activity
  Q(J,S,G,M)         Commodity g produced at j by facility s in month m
  A(I,KF,M)          Acres of kf in month m in county i
  X(I,KF,M)          Harvested biomass kf in county i month m
  XT(I,J,S,K,M)      Biomass k from i to facility size s at j in month m
  XP(J,S,K,M)        Biomass k processed by facility size s at j in month
m
  XSI(I,K,M)         Biomass k stored at source i in month m
  XSIP(I,K,M)        Biomass k going into storage at source i in month m
  XSIN(I,K,M)        Biomass k coming out of storage at source i in month
m
  XSJ(J,S,K,M)       Biomass k stored at facility location j in month m
  HU                 Total number of harvest unit
  HUM                Number of Harvest Units FOR MOWING
  HUB                Number of Harvest Units FOR BALING
  XHUM(I,M)          Harvest Unit FOR MOWING in county i in month m
  XHUB(I,M)          Harvest Unit FOR BALING in county i in month m
  BETA(J,S)          Zero-one variable for plant size s at j

POSITIVE VARIABLES Q, A, XT, XP, XSI, XSIP, XSIN, XSJ,X, XHUM, XHUB;
BINARY VARIABLE BETA;
INTEGER VARIABLE HUM, HUB ;
EQUATIONS
  OBJ                Objective function
  LANDCON1(I)        Constraint for cropland at county i
  LANDCON2(I,K)      Constraint for pastureland at county i
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  XCOMP(I,K,M)      Compute harvested biomass from harvested land
  ACRES0(I,K,M)     "Acres harvested when YAD(K,M)=0"
  BIOSUP(I,K,M)    "Each months' biomass supply balance at county i"
  BIOFLOW(M)        Biomass flow in each month
  BIOBALI(I,K)      Biomass balance at the supplying county
  PLTCAP(J,S,E,M)  Plant capacity constraints in gallons of ethanol
  STOCAPJ(J,S,M)    Biomass storage capacity constraint at the plant
  BIOXPJ(J,S,K,M) "Each months' biomass supply at location j"
  BIOBALJ(J,S,K)    Biomass balance at the plant
  OUTSUP(J,S,G,M)  Output supply constraint
  HUBLM(M)          Harvest Units balance for Mowing
  HUBLB(M)          Harvest Units balance for Baling
  TTONSHMM(I,M)     Capacity of harvest unit for Mowing in tons by
county and
                 month
TTONSHMB(I,M)    Capacity of harvest unit for Baling in tons by county
and
                 month
MXPLT            Max of one plant;

OBJ..  NPW =E= -SUM((J,S,FT),AFC(S,FT)*BETA(J,S))+[{SUM[M,(SUM((J,S,G),
RHO(G)*Q(J,S,G,M))-SUM((I,K), TPOC(K)*SUM(KF$KKF(K,KF), A(I,KF,M)))
               -SUM((I,KF), NCOST(KF,M)*A(I,KF,M))
               -SUM ((I,KF),PCOST(KF,M)*A(I,KF,M))
               -SUM((I,J,S,K), TAU(I,J)*XT(I,J,S,K,M))
               -SUM((I,K), GAMMA(K)*XSIP(I,K,M))
               -SUM((I,K), PSI(K)*SUM(KF$KKF(K,KF), X(I,KF,M))))]
               -SUM((J,S,FT), OMAP(S,FT)*BETA(J,S))
               -OMEGAM*HUM-OMEGAB*HUB}*PVAF];

LANDCON1(I)..          SUM(M, SUM(K$CRS(K),
SUM(KF$KKF(K,KF),A(I,KF,M))))
                       -BIPROP*POTACRES(I,"Cropland") =L= 0;

LANDCON2(I,K)$(ORD(K) NE 1)..      SUM(KF$KKF(K,KF), SUM(M, A(I,KF,M)))
                                 -BIPROP1*POTACRES(I,"Cropast") =L= 0;

XCOMP(I,K,M)..                   SUM(KF$KKF(K,KF), X(I,KF,M))-
                                   SUM(KF$KKF(K,KF), A(I,KF,M)*
                                   BYLD(I,KF))*YAD(K,M)=E=0;

ACRES0(I,K,M)$(YAD(K,M) EQ 0)..  SUM(KF$KKF(K,KF), A(I,KF,M))=E=0;

BIOSUP(I,K,M)$M2(M)..             SUM(KF$KKF(K,KF), X(I,KF,M))
+THETAI(K)*XSI(I,K,M-1)-SUM((J,S), XT(I,J,S,K,M))-XSI(I,K,M) =E= 0;

BIOFLOW(M)..               SUM([I,KF], X(I,KF,M))-SUM([I,J,S,K],
XT(I,J,S,K,M))
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                           +SUM([I,K], XSIN(I,K,M))-SUM([I,K],
XSIP(I,K,M))=E= 0;

BIOBALI(I,K)..                       SUM(KF$KKF(K,KF), SUM(M, X(I,KF,M)))
                                     -SUM([J,S,M], XT(I,J,S,K,M))
                                     -(1-THETAI(K))*SUM(M, XSI(I,K,M))
=E=0;

PLTCAP(J,S,E,M)..                    Q(J,S,E,M)-CAPP(S)*BETA(J,S)=L=0;

STOCAPJ(J,S,M)..                     SUM(K, XSJ(J,S,K,M))
                                     -CAP(S,"STORAGE")*BETA(J,S)=L=0;

BIOXPJ(J,S,K,M)$M2(M)..             SUM(I, XT(I,J,S,K,M))
                                     +THETAJ(K)*XSJ(J,S,K,M-1)
                                     -XSJ(J,S,K,M)-XP(J,S,K,M) =E= 0;

BIOBALJ(J,S,K)..                     SUM([I,M], XT(I,J,S,K,M))
                                     -(1-THETAJ(K))*SUM(M, XSJ(J,S,K,M))
                                     -SUM(M, XP(J,S,K,M))=E=0;

OUTSUP(J,S,G,M)..                    Q(J,S,G,M)
                                     -SUM(K, LAMBDA(K,G)*XP(J,S,K,M))=L=
0;

HUBLM(M)..                          SUM(I, XHUM(I,M))- HUM =L= 0;

HUBLB(M)..                          SUM(I, XHUB(I,M))- HUB =L= 0;

TTONSHMM(I,M)..                     SUM(KF, X(I,KF,M)) -
(XHUM(I,M)*CAPHUM(I,M)) =L= 0;

TTONSHMB(I,M)..                     SUM(KF, X(I,KF,M)) -
(XHUB(I,M)*CAPHUB(I,M)) =L= 0;

MXPLT..                          SUM([J,S], BETA(J,S)) =L= 1;

HUM.UP=200;

HUB.UP=200;

MODEL Ethanol /ALL/;

SOLVE Ethanol MAXIMIZING NPW USING MIP;

DISPLAY RHO, BETA.L, Q.L, XP.L, XSJ.L, XT.L, X.L, XSI.L, XSIN.L,
XSIP.L,
        A.L, XHUM.L, XHUB.L;
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***RESULTS SUMMARY***

PARAMETER TXHUM Total harvest unit for mowing activity by month;
  TXHUM(M) = SUM(I, XHUM.L(I,M));

PARAMETER TXHUB Total harvest unit for baling activity by month;
  TXHUB(M) = SUM(I, XHUB.L(I,M));

PARAMETER TOTLAND Total land producing biomass;
  TOTLAND(K,M) = SUM(KF$KKF(K,KF), SUM(I, A.L(I,KF,M)));

PARAMETER TLANDM Total land producing biomass by month;
  TLANDM(M) = SUM([I,KF], A.L(I,KF,M));

PARAMETER TLANDK Total land producing biomass by biomass type;
  TLANDK(K) = SUM(KF$KKF(K,KF), SUM([I,M], A.L(I,KF,M)));

PARAMETER TLANDRK Total area harvested annually by region and feedstock
type;
  TLANDRK(R,K) = SUM(I$IR(I,R), SUM(KF$KKF(K,KF), SUM(M,
A.L(I,KF,M))));

PARAMETER TLANDR Total area harvested annually by region;
  TLANDR(R) = SUM(K, TLANDRK(R,K));

PARAMETER TOTBIO Total biomass to be made available annually (tons);
  TOTBIO = SUM([I,KF,M], X.L(I,KF,M));

PARAMETER MBIOHAR Total biomass harvested by month;
  MBIOHAR(M) = SUM([I,KF], X.L(I,KF,M));

PARAMETER TBIOK Total biomass harvested by biomass type;
  TBIOK(K) = SUM(KF$KKF(K,KF), SUM([I,M], X.L(I,KF,M)));

PARAMETER IKBIOHAR Total biomass harvested by county;
  IKBIOHAR(I,K) = SUM(M, SUM(KF$KKF(K,KF), X.L(I,KF,M)));

PARAMETER IMBIOHAR Total biomass harvested by county by month;
  IMBIOHAR(I,M) =  SUM(KF, X.L(I,KF,M));

PARAMETER AKBIOHAR Total biomass harvested acres by county;
  AKBIOHAR(I,K) = SUM(M, SUM(KF$KKF(K,KF), A.L(I,KF,M)));

PARAMETER MBIOSTO Total biomass stored at counties by month;
  MBIOSTO(M) = SUM([I,K], XSI.L(I,K,M));
PARAMETER MBIOSTON Total biomass going in storage at counties by month;
  MBIOSTON(M) = SUM([I,K], XSIP.L(I,K,M));

PARAMETER MBIOSHIP Total biomass shipments by month;
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  MBIOSHIP(M) = SUM([I,J,S,K], XT.L(I,J,S,K,M));

PARAMETER BIOSHIP Biomass shipments from counties to plants by type and
month;
  BIOSHIP(K,M) = SUM([I,J,S], XT.L(I,J,S,K,M));

PARAMETER BIOSHIPIJ Biomass shipments from county i to plant j;
  BIOSHIPIJ(I,J) = SUM([S,K,M], XT.L(I,J,S,K,M));

PARAMETER PLTR Optimal plant locations by region;
  PLTR(J,R)$JR(J,R) = SUM(S, BETA.L(J,S));

PARAMETER MBIOSTJ Total biomass stored onsite;
  MBIOSTJ(M) = SUM([J,S,K], XSJ.L(J,S,K,M));

PARAMETER PROPCAPM "Plant monthly capacity usage (percent)";
  PROPCAPM(J,S,M) = 100*Q.L(J,S,"Ethanol",M)/CAPP(S);

PARAMETER PROPCAP "Plant monthly capacity usage (percent)";
  PROPCAP(J,S) = 100*SUM(M, Q.L(J,S,"Ethanol",M))/(12*CAPP(S));

DISPLAY TOTLAND, TLANDM, TLANDK, TLANDRK, TLANDR, TOTBIO, MBIOHAR,
TBIOK,
        IKBIOHAR, IMBIOHAR,AKBIOHAR, MBIOSTO, MBIOSTON, MBIOSHIP,
BIOSHIP,
        BIOSHIPIJ, PLTR, MBIOSTJ,PROPCAPM, PROPCAP, TXHUM, TXHUB;

PARAMETER PRODCO "Total feedstock production/procurement costs in $";
  PRODCO = SUM([I,K,M], TPOC(K)*SUM(KF$KKF(K,KF), A.L(I,KF,M)));

PARAMETER LDCO Land rent and opportunity cost of crop residues in $;
  LDCO = SUM([I,K,M], POC(K,"Landrent")*SUM(KF$KKF(K,KF), A.L(I,KF,M)))
            +SUM([I,K,M], POC(K,"Biopcost")*SUM(KF$KKF(K,KF),
A.L(I,KF,M)));

PARAMETER ESMCO "Establishment/maintenance cost, w/o landrent or cost
of N";
  ESMCO = PRODCO - LDCO;

PARAMETER NITCO Total cost of nitrogen fertilizer in US $;
  NITCO = SUM([I,KF,M], NCOST(KF, M)*A.L(I,KF,M));

PARAMETER PITCO Total cost of phosphorus fertilizer in US $;
  PITCO = SUM([I,KF,M], PCOST(KF, M)*A.L(I,KF,M));

PARAMETER FLDCO "Total field costs, excluding landrent & cost of crop
          residues";

  FLDCO = ESMCO + NITCO+PITCO;
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PARAMETER TPTCO Total cost of transporting the feedstocks;
  TPTCO = SUM([I,J,S,K,M], TAU(I,J)*XT.L(I,J,S,K,M));

PARAMETER STORCO Total cost of storing biomass in the field;
  STORCO = SUM([I,K,M], GAMMA(K)*XSIP.L(I,K,M));

PARAMETER FXDCO(FT) Fixed costs by facility type at year 0-Initial
          Investment;

FXDCO(FT)$(ORD(FT) EQ 2) = SUM([J,S], AFC(S,"PROCESS")*BETA.L(J,S));

PARAMETER OMDCO(FT) O & M costs by facility type-Same for year 1 to 20;

OMDCO(FT)$(ORD(FT) EQ 2)= SUM([J,S],OMAP(S,"PROCESS")*BETA.L(J,S));

PARAMETER TFXDCO Total fixed costs;

TFXDCO = SUM(FT, FXDCO(FT));

PARAMETER TOMDCO Total O & M costs;
TOMDCO = SUM(FT, OMDCO(FT));

PARAMETER HRVUNTSM   Harvest Units FOR MOWING to be purchased;
        HRVUNTSM = HUM.L;

PARAMETER HRVUNTSB   Harvest Units FOR BALING to be purchased;
        HRVUNTSB = HUB.L;

PARAMETER HARVCO Total Cost of Harvesting using Harvest Units;
         HARVCO = OMEGAM*HUM.L+OMEGAB*HUB.L;

PARAMETER TPCOST Total Biomass Purchase Cost in $ per ton;
         TPCOST = SUM([I,K,M], PSI(K)*SUM(KF$KKF(K,KF), X.L(I,KF,M)));

DISPLAY LDCO, FLDCO, STORCO, TPTCO, FXDCO, TFXDCO, OMDCO, TOMDCO;

DISPLAY ESMCO, NITCO, PITCO, PRODCO, HRVUNTSM, HRVUNTSB, HARVCO,
TPCOST;
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VITA

Mohua Haque

Candidate for the Degree of

Doctor of Philosophy

Thesis: SWITCHGRASS BIOMASS TO ETHANOL PRODUCTION ECONOMICS: FIELD TO FUEL APPROACH

Major Field: Agricultural Economics

Biographical:

Education: Completed the requirements for the degree of Doctor of Philosophy in Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma in December, 2010.Received Master of Science degree in Agribusiness and Applied Economics from the North Dakota State University, Stillwater, OK in December, 2007. Received Master of Social Science degree in Economics from the University of Dhaka, Dhaka, Bangladesh in November, 2000. Received Bachelor of Social Science degree in Economics from the University of Dhaka, Dhaka, Bangladesh in June, 1999.

Experience: Graduate Research Assistant in the Department of Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma, Jan 2007- Dec 2010; Graduate Research and Teaching Assistant in the Department of Agribusiness and Applied Economics at the North Dakota State University, Fargo, North Dakota, Aug 2005-Aug 2006. Student Consultant, Information Technology Service (ITS) North Dakota State University, Fargo, North Dakota, Jan 2005- Dec 2006. Officer, Foreign Exchange and Trade, Bank Asia Limited, Dhaka, Bangladesh, June 2001-Nov 2004

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Name: Mohua Haque Date of Degree: December, 2010

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: SWITCHGRASS BIOMASS TO ETHANOL PRODUCTION ECONOMICS: FIELD TO FUEL APPROACH

Pages in Study: 153 Candidate for the Degree of Doctor of Philosophy

Major Field: Agricultural Economics

Scope and Method of Study: Switchgrass has been proposed as a dedicated energy crop. The first essay determines switchgrass yield response to nitrogen fertilizer for a single annual harvest in July and for a single annual harvest in October based on a field experiments conducted at Stillwater, OK. Data were fitted to several functional forms to characterize both the July harvest and the October harvest response functions. Extending the harvest window to take advantage of reduction in harvest machinery investment costs has important biological consequences. The second essay determines the cost to deliver a ton of switchgrass biomass to a 2,000 tons per day plant located in Oklahoma. The model accounts for differences in yield and nitrogen fertilizer requirements across harvest months. The data were incorporated into a multi-region, multi-period, monthly time-step, mixed integer mathematical programming model that was constructed to determine the optimal strategy. Desirable feedstock properties, biomass to biofuel conversion rate, and investment required in plant differs depending on which conversion technology is used. The third essay determines the breakeven ethanol price for a cellulosic biorefinery. A comprehensive mathematical programming model that encompasses the chain from land acquisition to ethanol production was constructed and solved.

Findings and Conclusions: The July and October harvest plateau yield of 4.36 and 5.49 tons per acre were achieved with an estimated annual nitrogen fertilizer application of 80 and 63 pounds per acre, respectively. Farm gate production costs were estimated to be $60 per ton for the July harvest and $50 per ton for the October harvest. Based on the model results, the strategy of extending harvest over many months is economically preferable to a strategy of harvesting only in peak yield harvest months. Restricting harvest to a two-month harvest season would increase the cost to deliver feedstock by 23 percent. For a capital requirement of $400 million for a 100 million gallons per year biorefinery and a conversion rate of 100 gallons of ethanol per dry ton, the breakeven ethanol price is $1.93 per gallon. Biomass to ethanol conversion rate and the cost of biorefinery construction, operation, and maintenance are critical issues in the determination of the cost of producing ethanol from switchgrass.

ADVISER'S APPROVAL: Francis Epplin