Managing Expected Switchgrass Biomass Yield Variability by Strategically Selecting Land to Lease

Deepayan Debnath, Arthur L. Stoecker, and Francis M. Epplin

Deepayan Debnath is a graduate research assistant, Arthur L. Stoecker is associate professor, and Francis M. Epplin is professor and Jean & Patsy Neustadt Chair, Department of Agricultural Economics, Oklahoma State University. Support for this project was provided by the USDA NIFA Biomass Research and Development project number 0220352. This project is also supported by the USDA NIFA Hatch grant number H-2824, and by the Oklahoma Agricultural Experiment Station, and by the Jean & Patsy Neustadt Chair. Support does not constitute an endorsement of the views expressed in this paper by the USDA.

Selected paper prepared for presentation at the Agricultural & Applied Economics Association's 2012 AAEA Annual Meeting, Seattle, Washington, August 12-14, 2012

Abstract

Biorefineries that plan to use switchgrass exclusively will have to account for year-to-year variability in feedstock production. The objective of this research is to determine the quantity, class, and location of land to lease for switchgrass production to provide for the needs of a biorefinery. The firm could elect to lease land based on average switchgrass yields or to lease to attempt to insure that even in the worst case (based on historical data) production year the area leased will produce sufficient feedstock to fully provide for the needs of the biorefinery. EPIC was used to generate empirical distributions of switchgrass biomass yields for three land classes for each of 30 counties. Mathematical programming was used to address the objectives and to determine the tradeoff between quantity of land to lease and the daily cost of idling the biorefinery. Leasing sufficient land to ensure adequate feedstock in every state of nature increases the land requirement by 21% and delivered feedstock cost by 7%.

Introduction

In anticipation of an economically viable feedstock production and conversion system, the U.S. Energy Independence and Security Act of 2007 included a provision that by 2022, that if produced, 16 billion gallons of cellulosic biofuels be marketed. To-date the standard paradigm for evaluating the economics of cellulosic biofuels has followed the pattern used to evaluate grain ethanol. However, producing, harvesting, storing, and delivering cellulosic biomass such as switchgrass and converting it to biofuel is fundamentally different than 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. Initially, the quantity of corn used by ethanol plants relative to total global corn production was relatively small. In bumper crop years as well as short crop years, corn ethanol biorefinery managers may bid corn grain from alternative uses. Except for having to pay higher prices, they don't have to be overly concerned about the risk of idling the biorefinery due to a short crop. A similar feedstock production and delivery infrastructure does not exist for the anticipated cellulosic biomass biorefineries.

Year round operation of a switchgrass biorefinery will require year round delivery of switchgrass feedstock. Prior to investing $400-$700 million in a cellulosic biorefinery, prudent investors would expect assurance that a flow of feedstock that meets the quality standards of the facility will be available at a cost that provides a high probability of a good investment. It is unlikely that they would rely on spot markets to procure feedstock. One potential strategy would be for the biorefinery to engage in long term land leases and to manage the production, harvest, storage, and delivery of feedstock. They could identify and lease a sufficient quantity of land in the vicinity of the biorefinery to provide for the expected feedstock needs. However, switchgrass yields vary from year-to-year. And, if all land that is contracted for production is in close proximity to the biorefinery, in bad weather years, yields across the region may be low and insufficient to meet the needs of the biorefinery. In good weather years, yields may be greater than expected and more biomass may be produced than can be processed. However, some fields within the region may experience greater than average yields and other not too distant fields, lower than average yields in the same year. If yields across fields within the potential biorefinery supply shed are not highly correlated, a biorefinery might attempt to reduce overall year-to-year variability in feedstock production by strategically selecting a portfolio of land to lease.

Given the absence of a biomass spot market, the biorefinery management team must determine the quantity and location of land to contract for switchgrass production. If they contract for insufficient land, in some years switchgrass production will be inadequate to provide for the total annual feedstock needs. In this case the biorefinery will be forced to shut down for a period of time. Each idled day for lack of feedstock will have economic consequences. The net cost of a forced idle day will depend on the lost revenue as well as on production costs that can't be avoided. If, on the other hand the team contracts for too much land, the biorefinery will be responsible for cost of leasing more acres than necessary. The optimal strategy will depend on the cost of idling the plant relative to the cost of leasing additional land.

The biorefinery could plan to maintain a storage reserve from which biomass may be retrieved in low production years. However, there are a number of issues associated with maintaining the quality of switchgrass biomass for an extended period of time. The cost and efficiency of conversion for systems such as enzymatic hydrolysis depend on the characteristics of the feedstock. Maintenance of feedstock quality over an extended period of time may require expensive storage facilities and carry a substantial risk of loss from fire. Additionally, managing consecutive bad weather years could be challenging and require a large investment.

Prior studies have ignored the potential consequences of switchgrass yield variability on the economics of the biorefinery (Kazi et al., 2010; U.S. Department of Energy, 2011; Wright et al., 2010). To achieve cost economies, a biorefinery could be expected to strive to operate continuously throughout the year. In bad weather years, yields may be low and insufficient to meet the needs of the biorefinery. If weather is unfavorable for switchgrass production throughout the region such that there is an insufficient quantity of feedstock, the biorefinery may encounter forced downtime. In good weather years, yields may be greater than expected and more biomass may be produced than can be processed. Managing feedstock flows could be expected to be a critical issue. Disruptions in the flow of feedstock could result in substantial cost for the system.

This study is designed to address both year-to-year switchgrass yield variability and within year yield variability across Oklahoma counties. It is designed to establish an initial baseline under the assumption that maintenance of a strategic storage reserve would be impractical. The objective of this research is to determine (a) the quantity and location (county) of land to lease for an average switchgrass production year; (b) the quantity and location of land to lease to insure that in each production year the acres leased will produce sufficient feedstock to fully provide for the needs of the biorefinery even in the worst case (based on historical data) year; and (c) determine the tradeoff between the quantity of land to lease and the daily cost of idling the biorefinery.

Conceptual Model

This study is performed in three steps: (1) switchgrass biomass yield is calibrated and simulated using the Environmental Policy Integrated Climate (EPIC) model (Williams, Jones, and Dyke 1984); (2) GIS analysis is performed to determine the centroid of each land class type for each county surrounding the proposed biorefinery location to enable estimation of feedstock transportation cost; and (3) an economic optimization model is developed to determine the optimal quantity of land from each of three land classes to be leased in each county.

The calibrated EPIC model is validated by comparing the simulated switchgrass yields against the actual field trial yields obtained from experiments conducted at three locations over seven years. GIS analysis was performed to determine the centroid of each of the three land classes in each county and the nearest town to that location. Transportation distances were determined from the each centroid to the predetermined biorefinery location. Based on the switchgrass biomass yields, land leasing, production, harvest, and transportation costs, a mathematical programming model was built and solved to determine the economically optimal quantity and location of land for each land class to lease in each county to deliver 700,000 Mg of biomass annually to the predetermined biorefinery location. The model was first solved under the assumption that the mean level of switchgrass yield would be achieved every year (ignoring variability). The model was then solved to determine the quantity and location of land that would have been required to insure that at least 700,000 Mg could have been produced and delivered in each of the 50 years for which historical yields were simulated. Finally, the model was solved to trace out the tradeoff between the expected cost of idling the biorefinery for a day in response to insufficient feedstock, and the optimal quantity of land to lease.

Study Area and Data

The EPIC model was calibrated and validated for three locations for which data from experimental switchgrass field trials were available: Stillwater, Haskell, and Chickasha. The biorefinery was assumed to be located near Okemah in Okfuskee County (Figure 1). Thirty counties within a 200 km radius of the potential biorefinery were identified. Each of the 30 counties includes land that could potentially be leased by the biorefinery and used to produce switchgrass. Weather data for each county were obtained from the National Oceanic and Atmospheric Administration (NOAA) database and supplemented with data from local weather stations (MESONET). Soils data were obtained from the USDA NRCS Land Survey Geographic (SSURGO) database. Production practices for switchgrass establishment, maintenance, and harvest were obtained from Fuentes and Taliaferro (2002). These data were used to simulate switchgrass yields for each county based on the calibrated EPIC model for each of three land classes: I, II and III.

EPIC Model Calibration and Validation

Productivity, growth, longevity, and adaptation traits of switchgrass primarily depend on the geographical location of their origin. Based on the latitude and longitude of origin, switchgrass is broadly classified into two ecotypes, upland and lowland. Lowland ecotype varieties are more compatible to the southern latitude or southern part of the U.S. due to their ability to adapt to the longer growing season and warmer climatic conditions. Upland varieties are widely adapted in the northern part of the U.S. due to their greater potential to survive in the colder conditions of northern latitudes (Casler et al. 2007).

Lowland ecotype switchgrass yields were calibrated using EPIC v 0509 and validated against switchgrass biomass field trial yield data obtained from three locations: Chickasha, Haskell, and Stillwater (Fuentes and Taliaferro 2002; Haque, Epplin, and Taliaferro 2009). Calibration and validation of switchgrass yields were performed for each of the three different soil types: McLain silt loam, Taloka silt loam and Kirkland silt loam on which the field experiments at Chickasha, Haskell and Stillwater were conducted. Soil related information for these land types including bulk density, water, sand and silt content, organic carbon concentration, calcium carbonate content, saturated conductivity and cation exchange capacity were obtained from the SSURGO land database. The field trial data used to validate the calibrated results were obtained from a single annual harvest. Single harvest management practices starting from the second year, as conducted in the field experiments, were used to calibrate the EPIC model. Daily weather data of maximum temperature, minimum temperature, precipitation, solar radiation, relative humidity and wind speed for each location were obtained from MESONET (2011) and NOAA (2011).

Calibration required adjustments to the EPIC crop parameter (CROPCOM crop file in EPIC v 0509). Timing of leaf decline (DLAI, EPIC v 0509 crop parameter acronyms), and maximum leaf area index (DMLA) were adjusted to 0.75 and 6, respectively. Leaf area decline after anthesis (RLAD), rate of decline in biomass energy after anthesis (RBMD) and plant maturity (RWPC2) were adjusted to 0.1, 0.1 and 0.3, respectively (Thomson et al. 2009).

The Chickasha and Haskell field trials included three lowland ecotype switchgrass cultivars: Alamo, Kanlow and PMT 279. Measured yields of these cultivars were averaged and compared to the simulated yields. The Stillwater trials included only Alamo. EPIC simulated switchgrass yields were compared against the actual switchgrass yields. The simulated yields explained 67% of the variation in the measured yields for the 10 years (1994-2000 and 2003-2005). However, the model did not closely predict the Chickasha yields recorded for 1995. When the 1995 Chickasha observation was dropped, the R^2 increased to 0.84. By this measure, the model was assumed to have successfully captured the switchgrass biomass yield response and yield variation and was assumed to be calibrated (Table 1).

Epic Model Simulation

The calibrated EPIC model was used to simulate switchgrass biomass yields for 50 states of nature (1962-2011) for three land classes (Class I, II, and III) for each of 30 counties. The study was limited to land classes I-III based on the assumption that other land classes would not be suitable for economically viable production and harvest of switchgrass biomass. The soil classification within each land class type with the most hectares in the county was used in the EPIC simulation to represent the specific land class. In other words, it was assumed that all soil types in the county within a particular class produced identical yields in each simulated year. Soils information was obtained from the SSURGO database.

Daily weather data of solar radiation, maximum temperature, minimum temperature, relative humidity, wind velocity, and precipitation for each county were obtained from the MESONET data system from 1994 through 2011, and from the NOAA weather system for years 1962 through 2011.

Production practices budgeted to estimate the cost of switchgrass establishment, maintenance, and harvest were based on the no-till system described by Griffith, Epplin and Redfearn (2010). Switchgrass was assumed to be seeded, established, but not harvested, in year one. From years two onwards it was assumed to be fertilized with 78 kg of nitrogen per hectare per year and harvested once per year. It was assumed that one condition of the land lease is that the land owner will be responsible for the cost of any phosphorus and potassium fertilizer and lime necessary for adequate pH, and adequate soil levels of phosphorus and potassium prior to switchgrass establishment (Haque, Epplin, and Taliaferro 2009). The switchgrass biomass is assumed to be harvested (baled) once per year at the end of the growing season after the first frost and after most nutrients have translocated from the above ground to below ground parts of the plant.

Economic Optimization Model

A programming model was designed to minimize the cost to meet the expected annual biorefinery requirements and the cost of idling the plant in the event of insufficient feedstock. The objective function was optimized subject to available land, switchgrass biomass yield, and biorefinery requirements. Constraints that require biorefinery requirements to be fulfilled for each state of nature were incorporated into the model to determine if a portfolio of land could be identified across the 30 counties that would reduce the downside variability of switchgrass yield. The mathematical programming model is as follows:

$$\underset{X,BAL,RAK,TRN,Y,DAY}{Minimize}\ TC = \sum_{c=1}^{30}\sum_{s=1}^{3}\lambda_{c,s}X_{c,s} + \sum_{c=1}^{30}\sum_{s=1}^{3}\alpha RAK_{c,s} + \sum_{c=1}^{30}\sum_{s=1}^{3}\beta BAL_{c,s} + \sum_{c=1}^{30}\sum_{s=1}^{3}\Gamma_{c,s}TRN_{c,s} + \eta DAY \quad (1)$$

where, *TC* is the total costs ($) of producing, harvesting, and transporting biomass to a predetermined location and the cost of idling the plant in the event of insufficient biomass; $X_{c,s}$ is the hectares of land leased for switchgrass production in county *c* and land class type *s*; $\lambda_{c,s}$ is the production cost ($/ha) including establishment costs, land rent, fertilizer and mowing costs in county *c* and land class type *s*; α is the cost ($/ha) of raking; $RAK_{c,s}$ is the quantity (ha) of land raked in county *c* and land class type *s*; β is the cost ($/Mg) of baling and stacking switchgrass; $BAL_{c,s}$ is the quantity (Mg) of switchgrass baled and stacked in county *c* and land class type *s*; $\Gamma_{c,s}$ is the cost ($/Mg) of transporting switchgrass biomass from country *c* and land type *s* to the proposed biorefinery location; $TRN_{c,s}$ is the quantity (Mg) of switchgrass biomass transported from county *c* and land type *s* to the biorefinery location; η is the per day cost of idling the plant; *DAY* is the number of days in an average year the biorefinery is not operating due to lack of feedstock. Raking and baling activities are considered separately, since the cost of raking depends on the hectares of land raked while baling costs are a function of yield. Equation (1) is minimized subject to a set of constraints as follows:

$$X_{c,s} \le LAND_{c,s} \quad (2)$$

$LAND_{c,s}$ is available land in county *c* and land class type *s* assumed to be available for leasing. For the present study land assumed to be available for leasing was set equal to 10% of the total quantity of land class type *s* in county *c;* and $X_{c,s}$ is the hectares of land leased for switchgrass production in county *c* and land class type *s*.

$$RAK_{c,s} - X_{c,s} \le 0 \quad (3)$$

$RAK_{c,s}$ is the hectares of land raked in county *c* and land type *s*. Land in a given state of nature that is not required to meet biorefinery needs is not raked. It is assumed that all the established switchgrass hectares are mowed once per year. For a state of nature in which production from the total land leased exceeds biorefinery requirements, it is assumed that excess production would be mowed and left in the field to decompose and build organic matter.

$$BAL_{c,s} - AVGYLD_{c,s} RAK_{c,s} \leq 0 \tag{4}$$

$BAL_{c,s}$ is the hectares of land baled in county *c* and land type *s*; $AVGYLD_{c,s}$ is the average switchgrass yield (Mg/ha) as simulated by EPIC from the 50 states of nature in county *c* and land class type *s*.

$$TRN_{c,s} - BAL_{c,s} \leq 0 \tag{5}$$

$$\sum_{c=1}^{30} \sum_{s=1}^{3} TRN_{c,s} \geq AnlRqmt \tag{6}$$

$TRN_{c,s}$ is the quantity (Mg) of switchgrass biomass transported from county *c* and land type *s* to the biorefinery location; *AnlRqmt* is the biorefinery's annual switchgrass feedstock requirement to operate at full capacity (700,000 Mg/yr)[1].

$$\sum_{c=1}^{30} \sum_{s=1}^{3} AnlYLD_{t,c,s} X_{c,s} + Y_t \geq AnlRqmt \quad \forall t = 1, \ldots, 50 \tag{7}$$

$$\sum_{t=1}^{50} Y_t \Pr ob_t - \partial DAY \leq 0 \tag{8}$$

where, $AnlYLD_{t,c,s}$ is the switchgrass yield (Mg/ha) obtained from EPIC simulation using the historical weather data and soils information for county *c* and land class type *s* in state of

---

[1] When the requirement is imposed that 700,000 Mg be produced in each state of nature, the model calculates and includes the cost to rake and transport based on the average yield. In years when weather and yields are better than average it would be optimal to harvest those acres closest to the biorefinery and save transportation cost. In the worst weather year, harvest would be required to include fields more distant from the biorefinery and the transportation cost would be greater than average. The raking and transportation cost would be different for each state of nature. The model is being revised to address this concern.

nature t; Y_t is the deviation in switchgrass production below the annual requirement (Mg/ha) in state of nature t; $Prob_t$ is the probability of a state of nature t (if each state of nature is assumed to be equally likely, $Prob_t$ is set equal to $1/n$ where n is equal to the number of states of nature (50)); and δ is the biorefinery's per day switchgrass feedstock requirement. All the choice variables are restricted to be nonnegative:

$$X, RAK, BAL, TRN, Y \geq 0 \tag{9}$$

The USDA (2011) cash rental rate which is the market based estimate of the opportunity cost of land is used as the land rental cost. The estimated rent cost for each land class type (I, II, and III) for each county was obtained by extrapolating the USDA cropland rental values using equation 10. Land rent cost for each land class type in each county was estimated to be:

$$\omega_{c,s} = YLD_{c,s}\left(\frac{\sum_{s} X_{c,s} Z_c}{\sum_{s} YLD_{c,s} X_{c,s}}\right) \tag{10}$$

where, $\omega_{c,s}$ is the rental value of a hectare of land in county c and land class type s; $YLD_{c,s}$ is the potential wheat yield in county c and land class type s as reported in the SSURGO data base, and; $X_{c,s}$ is the available hectares of land in county c and land class type s; Z_c is the USDA cropland rental value for the county c.

Estimates of switchgrass production and harvest costs were taken from Turhollow and Epplin (2012). The centroid of each land class type in each county was determined and the nearest town to the corresponding land class centroid was obtained by performing GIS analysis (Figure 1). Road distance between the town and the predetermined biorefinery location (Okemah, Okfuskee) was obtained from Google maps (maps.google.com). Transportation costs were calculated based on an equation modified from data reported by Wang (2009).

$$\Gamma_{c,s} = 0.8796 + 0.1983 d_{c,s} \tag{11}$$

where Γ_c is the estimated transportation costs in U.S. dollars for transporting a Mg of switchgrass dry mass from land class type s of county c to the biorefinery location; $d_{c,s}$ is the one way distance (km) between the centroid of land class type s of county c and the biorefinery location.

Based on estimates provided by Kazi et al. (2010) and Wright et al. (2010) the biorefinery daily requirement of feedstock was set equal to 2,000 Mg. Assuming down time requirement for maintenance the biorefinery is expected to process feedstock 350 days per year, resulting in an annual feedstock requirement of 700,000 Mg. Each idled day for lack of feedstock will have economic consequences. The net cost of a forced idle day will depend on the lost revenue as well as on production costs that can't be avoided. Lost revenue from not producing biofuel can be estimated. For a conversion rate of 99 gallons per Mg, the biorefinery with a daily feedstock requirement of 2,000 Mg would produce 198,450 gallons of ethanol. For a wholesale ethanol price of \$2.14 per gallon (USDA 2012) the idling costs from the lost revenue would be \$424,683 per day (an estimate of the value of η in equation (1)). Since not all production costs can be avoided if the plant is idled for a day, this can be interpreted as a lower bound estimate of the daily idling cost.

Results

Initially the model was solved under the assumption that the average yield is produced in each state of nature. This was accomplished by setting η in equation 1 equal to zero. Results obtained from the optimization model suggest that if a potential biorefinery is built near Okemah in Okfuskee County with an annual switchgrass biomass feedstock requirement of 700,000 Mg, in a year in which the switchgrass yields are average, the biorefinery will require 50,128 ha with an estimated delivered switchgrass feedstock cost of \$60 Mg^{-1} (Table 2). However, if these

50,128 ha were leased, in 25 of the 50 states of nature, the total yearly biomass demand would not be met. On average the lack of feedstock would force the plant to be idle for an average of 16 days per year. Table 3, shows that the potential biorefinery would optimally lease land class I, II, and III in Creek, Hughes, McIntosh, Okfuskee, Okmulgee, Pittsburg, and Seminole counties, while land class I and II would be leased in Lincoln county, and only land class I leased in Pottawatomie county (Figure 2)**.** These findings follow from the assumption that the 50 years of data appropriately represents the entire switchgrass yield distribution.

Next the model was solved with η in equation 1 equal to M where M is a sufficiently large penalty on idling the plant to insure that 700,000 Mg be produced in each state of nature. If the biorefinery management chose to attempt to lease sufficient land so that the required feedstock would be available for each year, then 60,639 ha would be leased, resulting in an increase in the costs of delivered feedstock from \$60.07 to \$64.15 Mg^{-1}. Table 4 shows the relative change in quantity and location of land leased if the model is solved to meet the 700,000 Mg requirement in each state of nature rather than an average of 700,000 Mg. The revised system would optimally lease an additional 10,511 ha. Additional land would be leased in Coal (999 ha), Haskell (65 ha), Johnston (107 ha), Muskogee (2,522 ha), Oklahoma (2,882 ha) and Wagoner (7,383 ha) counties. However, less land would be leased in Lincoln (2,895 ha) and McIntosh (552 ha) counties. The net additional hectares of land are used in case of bad weather years. As noted, for those states of nature in which production from the total leased acres exceeds biorefinery requirements, it is assumed that excess production would be mowed and left in the field to decompose and build organic matter. The quantity of switchgrass baled and transported does not change from year-to-year. It is fixed based on the daily biorefinery biomass requirement. Therefore, while 60,639 ha are leased and mowed each year, with η in equation 1 equal to M, only the biomass from 49,976 ha of land is raked, baled, and transported.

When the value of η in equation 1 is changed from zero to M, the expected annual cost to deliver 700,000 Mg increases by \$2,852,973 (\$4.08/Mg). This could be interpreted as the cost of a pseudo self insurance policy to attempt to prevent idling the biorefinery due to insufficient feedstock. The success of this strategy depends on the validity of the assumption that the 50 years of data appropriately represents the entire switchgrass biomass yield distribution.

As noted, the value of η in equation 1 is a measure of the cost of a force idling the plant for a day due to insufficient feedstock. An idling plant relinquishes the opportunity to produce. The total cost for idling depend on the value of the products not produced and sold and the production costs that cannot be avoided even though the plant is idle. For a conversion rate of 99 gallons per Mg, the biorefinery with a daily feedstock requirement of 2,000 Mg would produce 198,000 gallons of biofuel. By this measure, for each \$1/gallon biofuel value the idling costs from the lost revenue would be \$198,000 per day. Since not all production costs can be avoided if the plant is idled for a day, this can be interpreted as a lower bound estimate of the daily idling cost. The value of η in equation 1 can be parameterized to trace out the tradeoff between the cost of idling the plant for a day and the optimal quantity of land to lease. Results are reported in Table 5.

The results suggest that if the cost of idling the biorefinery is \$424,683 per day based on producing ethanol as the single product and a wholesale ethanol price of \$2.14 (USDA, 2012) then the biorefinery would optimally lease 56,637 ha. This would result in average of two days per year during which the biorefinery would be idled due to insufficient feedstock.

The tradeoff between ethanol price and optimal quantity of land leased by the biorefinery is shown in Table 5. As the daily downtime cost of the biorefinery increases the optimal quantity of land to lease will also increase. As the price of the biofuel increases the cost of idling the plant increases. There is a clear tradeoff between the biorefinery downtime costs and the optimal quantity of land to lease (Figure 3). As more land is leased, the average number of days per year that the plant will be idled declines (Figure 4).

Conclusions

Based on the location of the study and the assumptions of the model, if a biorefinery that required 2,000 Mg of switchgrass biomass per day leased land based on average yields, in half of the years biomass production would be insufficient to meet the total needs. On average the biorefinery will be forced to shut down for 16 days per year due to the absence of switchgrass feedstock. Leasing sufficient land to ensure adequate feedstock in every state of nature increases the land requirement by 21% and delivered feedstock cost by 7%.

The study did not consider maintenance of a year-to-year storage reserve in biomass could be stored in better than average production years and from which biomass may be retrieved in low production years. At the present time what constitutes biomass quality and how that changes over time have not been fully resolved. Future research may be warranted to address year-to-year storage issue. Based on the results of this study, for a biorefinery that requires 700,000 Mg/year, the annual cost of establishing and maintaining a strategic year-to-year would have to be less than $2,852,973 to be more cost effective than leasing sufficient land to provide for biomass needs in even the worst state of nature.

References

Casler, M. D., K. P. Vogel, C. M. Taliaferro, N. J. Ehlke, J. D. Berdahl, E. C. Brummer, R. L.Kallenbach, C. P. West, and R. B. Mitchell. "Latitudinal and Longitudinal Adaptationof Switchgrass Populations." *Crop Science* 47(2007):2249-2260.

Epplin, F.M. ''Cost to Produce and Deliver Switchgrass Biomass to an Ethanol-Conversion Facility in the Southern Plains of the United States.'' *Biomass and Bioenergy* 11(1996):459–67.

Epplin, F.M., C.D. Clark, R.K. Roberts, and S. Hwang. ''Challenges to the Development of a Dedicated Energy Crop.'' *American Journal of Agricultural Economics* 89(2007):1296–302.

Epplin, F.M., and M. Haque. "Conversion of Millions of Acres to the Production of Biofuel Feedstock." *Journal of Agricultural and Applied Economics* 43, 2(2011):385-398.

Fuentes, R.G., and C.M. Taliaferro. ''Biomass Yields Stability of Switchgrass Cultivars.'' Trends in New Crops and New Uses. J. Janick and A. Whipkey, eds. Alexandria, VA: ASHS Press,2002, pp. 276–82.

Griffith, A.P., F.M. Epplin, and D.D. Redfearn. "Cost of Producting Switchgrass for Biomass Feedstock." Switchgrass Enterprise Budget, Oklahoma State University, 2010. Internet site: http://switchgrass.okstate.edu/enterprise-budget (Accessed November 2011).

Haque, M., F.M. Epplin, and C.M. Taliaferro. "Nitrogen and Harvest Frequency Effect on Yield and Cost for Four Perennial Grasses." *Agronomy Journal* 101(2009):1463-69.

Kazi, F.K., J.A. Fortman, R.P. Anex, D.D. Hsu, A. Aden, A. Dutta, and G. Kothandaraman.''Techno-economic Comparison of Process Technologies for Biochemical Ethanol Production from Corn Stover.'' Fuel 89(2010):S20–S28.

Khanna, M., B. Dhungana, and J.C. Brown.‘‘Costs of Producing Miscanthus and Switchgrassfor Bioenergy in Illinois.’’ *Biomass and Bioenergy* 32(2008):482–93.

NOAA, National Climatic Data Center, National Climatic Data Center. Daily weather data for Oklahoma 1985-1994. Inrernet site: http://gis.ncdc.noaa.gov/map/cdo/ (Accessed August 2011).

Oklahoma Climstological Survey. Oklahoma Mesonet: Daily weather data for Muskogee. 2011. Internet site: http://www.mesonet.org/index.php/weather/category/past_data_files (Acessed October 2011).

Perrin, R., K. Vogel, M. Schmer, and R. Mitchell. ‘‘Farm-Scale Production Cost of Switchgrass for Biomass.’’ *Bioenergy Research* 1(2008): 91–97.

Thomson, A. T., R. C. Izarrualde, T. O. West, D. J. Parrish, D. D. Tyler, and J. R. Williams.“Simulating Potential Switchgrass Production in the United States.” Pacific Northwest National Laboratory. DE-AC05-76RL01830, December 2009.

Turhollow, A.F. and F.M. Epplin. “Estimating Region Specific Costs to Produce and Deliver Switchgrass.” Chapter 8 in *Switchgrass: A Valuable Biomass Crop for Energy*. ed. Andrea Monti, New York: Springer Publishing Co. 2012.

U.S. Department of Agriculture, National Agricultural Statistics Service Land Values and Cash Rents. 2011. .Internet site: http://quickstats.nass.usda.gov/results/63D3252C-0498-3E63-99DD-20935377B67D (Accessed February 2012).

U.S. Department of Agriculture, Livestock & Grain Market News. National Weekly Ethanol Summary. 2012. Internet site: http://www.ams.usda.gov/mnreports/lswethanol.pdf (Accessed April 2012).

U.S. Department of Agriculture, *Land Service Geographic (SSURGO) Database for Oklahoma*. 2011. Internet site: http://lands.usda.gov/survey/geography/ssurgo/ (Accessed August 2011).

U.S. Department of Energy. 2011. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p.

Wang, C."Economic Analysis of Delivering Switchgrass to a Biorefinery from both the Farmers' and Processor's Perspectives." Master's thesis, The University of Tennessee, Knoxville, TN. 2009.

Williams, J.R., C.A. Jones, and P.T. Dyke. “A Modeling Approach to Determining the Relationship between Erosion and Land Productivity.*” Transaction of the American Society of Agricultural Engineers* 27(1984):129–144.

Wright, M.M., D.E. Daugaard, J.A. Satriob and R.C. Brown. ‘‘Techno-economic Comparison of Biomass-to-Biofuels Pathways.’’ Fuel 89,1 (2010):S2–S10.

Table 1: Comparison between measured and EPIC simulated lowland ecotype switchgrass yields

	Measured Yields	Simulated Yields
Mean (Mg/ha)	14.68	14.41
St. Dev.	4.29	4.16
Maximum (Mg/ha)	23.10	21.81
Minimum (Mg/ha)	7.28	7.57

Table 2. Total annual feedstock costs (land leasing, production, fertilization, harvest, and transportation), costs per Mg, area leased, and area harvested to deliver 700,000 Mg per year for three situations

	Total Feedstock Costs ($/yr)	Estimated Delivered Cost ($/Mg)	Land Required (ha)	Average Area Harvested (ha)
Best Yielding Year [a]	39,414,348	56.31	41,759	41,759
Average Yield	42,051,156	60.07	50,128	50,128
Insure 700,000 Mg in Every State of Nature [b]	44,904,129	64.15	60,639	49,976
Insure 700,000 Mg in Every State of Nature & Doubled Land Cost [b]	48,178,958	68.83	61,357	50,400

---

[a] If in every year the yield was equal to that obtained during the best state of nature, then only 41,759 ha would be required, and the estimated cost to deliver would be is $56.31/Mg.

[b] When the requirement is imposed that 700,000 Mg be produced in each state of nature, the model calculates and includes the cost to rake and transport based on the average yield. In years when weather and yields are better than average it would be optimal to harvest those acres closest to the biorefinery and save transportation cost. In the worst weather year, harvest would be required to include fields more distant from the biorefinery and the transportation cost would be greater than average. The raking and transportation cost would be different for each state of nature. The model is being revised to address this concern.

Table 3. Land leased in the counties and the corresponding land classes assuming average yield is achieved and ignoring year-to-year switchgrass yield variability

County	Land Class I (ha)	Land Class II (ha)	Land Class III (ha)
Creek	1,337	3,647	3,842
Hughes	329	2,645	6,348
Lincoln	251	2,895	
McIntosh	14	1,413	552
Okfuskee	774	1,057	3,154
Okmulgee	544	3,003	5,139
Pittsburg	142	2,744	5,938
Pottawatomie	669		
Seminole	120	1,329	2,242

Table 4. Change in location and type of land leased when moving from an average yield system to a full safety first system

County	Land Class I (ha)	Land Class II (ha)	Land Class III (ha)
Coal		999	
Creek			
Haskell	65		
Hughes			
Johnston	107		
Lincoln		-2,895	
McIntosh			-552
Muskogee			2,522
Okfuskee			
Oklahoma		2,882	
Okmulgee			
Pittsburg			
Pottawatomie			
Seminole			
Wagoner	773	2165	4445

Table 5. Ethanol price, corresponding biorefinery downtime costs, hectares of land leased and the number of days in an average year the biorefiney is forced to be idle

Ethanol Price ($/gal)	Downtime Costs ($ per day)	Land Leased (ha)	Idle Days
0.00	0	50,128	16
1.00	198,450	53,031	5
1.50	297,680	55,110	3
2.00	396,900	56,400	2
2.14	424,680	56,640	2
3.00	595,350	57,280	1

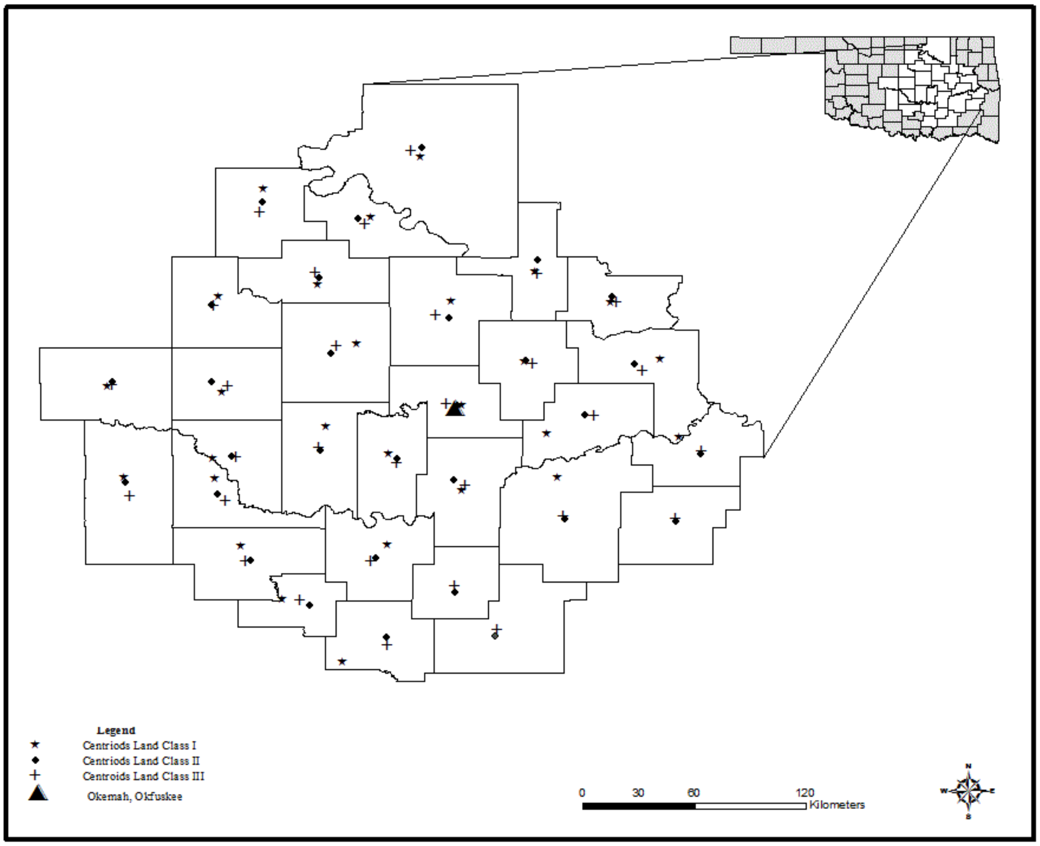
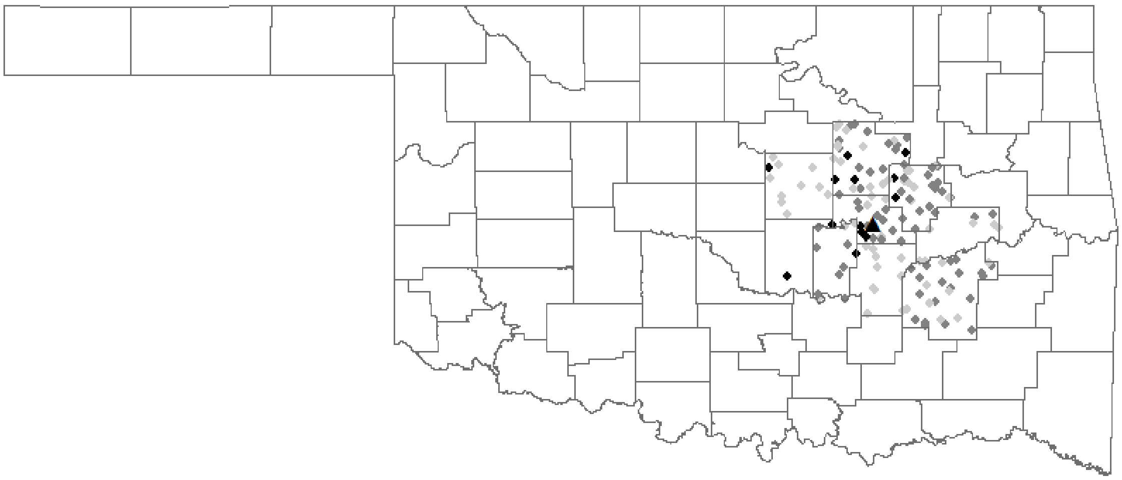


Figure 1. Map of Oklahoma showing the counties selected for potential switchgrass production.

Map of the centroids of land class I, II, and III in each of the thirty Oklahoma counties.

Land Leased Under Average Switchgrass Yield



Land Leased Under Year to Year Switchgrass Yield Variability

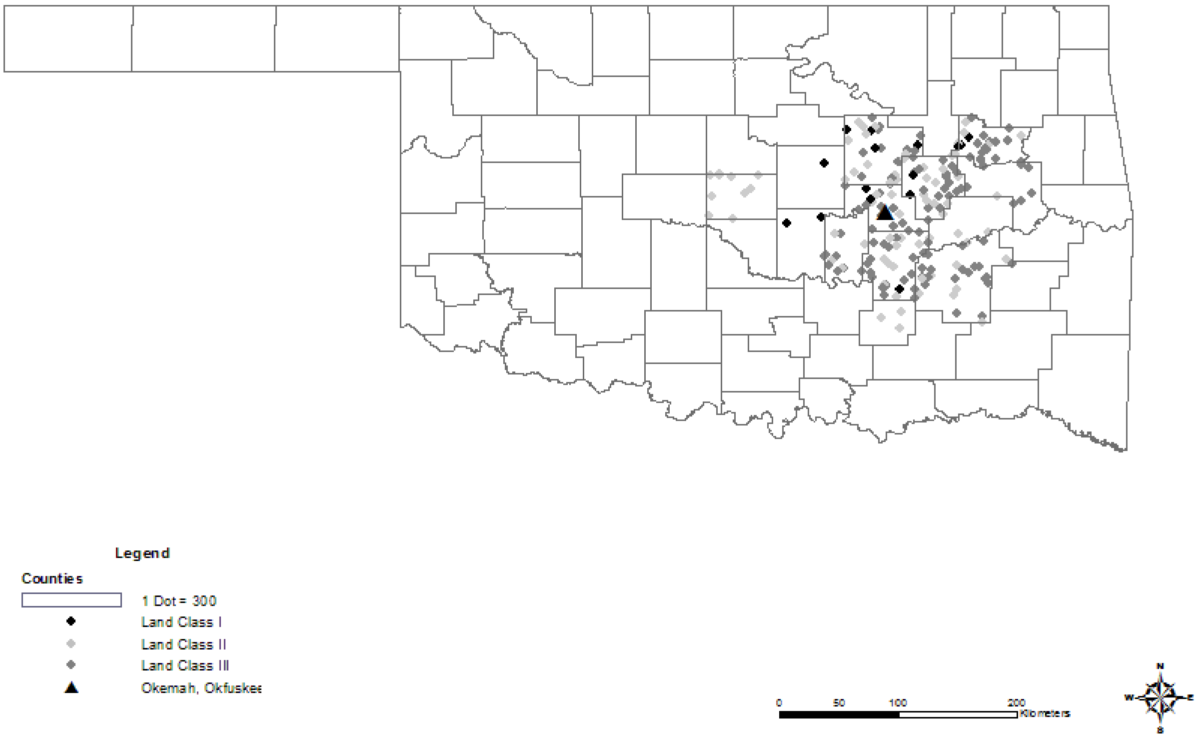


Figure 2. Location and land class leased by county. (Symbols randomly assigned within counties.)

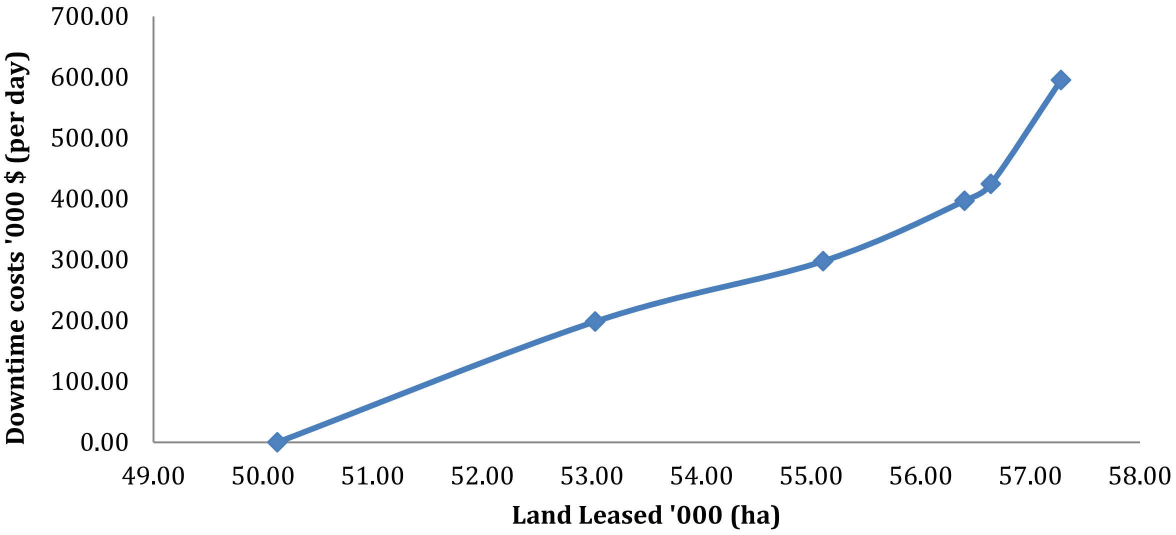


Figure 3. Tradeoff between the per day downtime costs of the biorefinery and the hectares of land leased

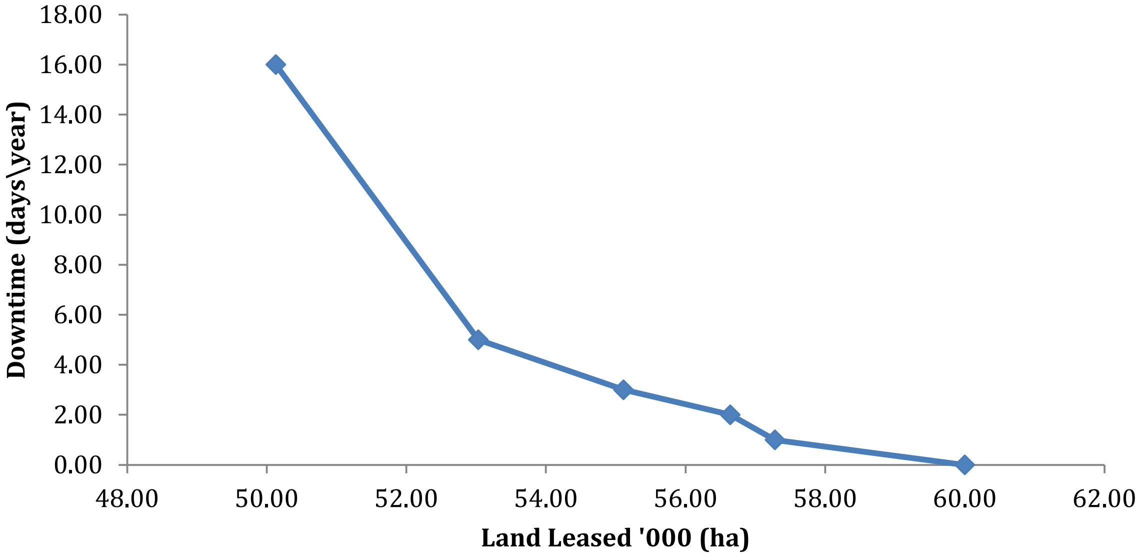


Figure 4. Tradeoff between the downtime days in an average year of the biorefinery and the hectares of land leased