Switchgrass Procurement Strategies for Managing Yield Variability: Estimating the Cost-Efficient D (Downtime Cost) L (Land to Lease) Frontier

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Abstract

Lignocellulosic biorefineries that plan to use switchgrass (*Panicum virgatum* L.) biomass exclusively will encounter both temporal (across years) and spatial (across locations within a given year) variability in feedstock production. Long term land leases could be employed to facilitate feedstock availability for the expected life of the biorefinery. If the quantity of land leased is based on average yields, in some years more biomass will be produced than can be processed. In other years feedstock production on the leased land may be insufficient to prevent biorefinery downtime. An optimal strategy for identifying which land to lease and seed to switchgrass, while considering yield variability and the opportunity cost of biorefinery downtime, is the focus of the research. The objective is to determine for a given biorefinery location the least-cost quantity, quality, and location of land to lease for alternative estimates of biorefinery downtime cost due to variable switchgrass yields. Fifty years of weather data are used to simulate switchgrass yield distributions for a case study region. An innovative mathematical programming model is developed and used to reveal the cost-efficient D (Downtime Cost) L (Land to Lease) frontier for a 2 Gg d⁻¹ biomass capacity biorefinery. If interyear storage is not permitted, 60,492 ha would be required to insure that the biorefinery run at full capacity every year given the estimated yield distributions. However, for some circumstances, it would be optimal to produce switchgrass on only 49,464 ha and idle the biorefinery for some days in low biomass production years.

Key words: Biorefinery; Biophysical model; DL frontier; Land lease; Switchgrass; Storage

1. Introduction

In 2007, the USA Congress passed the U.S. Energy Independence and Security Act (EISA). EISA mandates that, if produced, 60.57 hm³ of cellulosic biofuels be marketed annually by 2022 [1, 2]. To meet this mandate a significant quantity of lignocellulosic feedstocks from dedicated perennial energy crops such as switchgrass (*Panicum virgatum* L.) would be required.

Procurement of biomass from dedicated perennial energy crops such as switchgrass will be fundamentally different and much more challenging than procuring corn (*Zea mays* L.) grain. Schmidgall et al. [3] surveyed grain-ethanol biorefineries and found that 88% of respondents reported that they had easy access to feedstock and 91% reported that feedstock was readily available all of the time and could be obtained on the spot market. A similar feedstock production and delivery infrastructure does not exist for potential cellulosic biorefineries designed to use switchgrass biomass exclusively. Prior to investing millions of dollars in a biorefinery, due diligence would require a business plan for providing a flow of feedstock to the facility for its expected life. A single biorefinery would require that several thousand hectares within reasonable distance of the proposed biorefinery be bid from existing use and seeded to switchgrass.

Based on experience with the U.S. Conservation Reserve Program (CRP), U.S. land owners are willing to engage in long term contracts that provide an annual lease payment [4-7]. This history suggests that at some price substantial quantities of land could be bid from existing use. In the absence of government restrictions, a company could enter into long term leases with land owners and establish as many hectares of switchgrass as required for the biorefinery. Nickerson et al. [8] report that 44% of U.S. farm land is not owned by farmers. In some states less than half of farm land is owned by farmers. Many of these land owners could be expected to

be indifferent between leasing their land to farmers who use it to produce livestock or conventional crops, or to an integrated biorefinery that uses it to produce switchgrass biomass.

Long term land leases would facilitate coordination of switchgrass biomass production, harvest, and transportation logistics required to provide an efficient flow of feedstock. For example, a biorefinery designed to process 2 Gg d^{-1} would require 83 Mg per hour; approximately five truck loads every hour, 24 hours per day for the life of the biorefinery. Failure to provide feedstock would result in costly disruptions of biorefinery operations. If the annual feedstock requirements of the biorefinery and annual switchgrass yield were known with certainty, it would be straightforward to determine the number of hectares to lease. However, switchgrass biomass yields vary from year-to-year. In years with unfavorable switchgrass production weather, yields in the feedstock supply shed of the biorefinery may be low, and if too few hectares are leased, production from the leased hectares may be insufficient to meet the needs of the biorefinery. Since switchgrass biomass cannot be anticipated to be available from spot markets, the biorefinery may be forced to shut down for a period of time. Each idled day for lack of feedstock will have economic consequences. The net opportunity cost of a forced idle day (downtime cost) will depend on the lost revenue as well as on fixed production costs that cannot be avoided.

Selection of a biorefinery location and identification of land to lease for the production of feedstock will be critical decisions in determining the economic success of a switchgrass biomass processing facility. Prior research has developed methods for determining optimal biorefinery locations [9-12]. Case studies have been conducted to determine feedstock production locations when expected switchgrass yields are assumed to be the same in each field

each year [13-22]. However, most of these studies have ignored both temporal (year-to-year) and spatial (across fields within year) switchgrass yield variability.

Debnath et al. [23] considered switchgrass yield variability and developed a model that could be used for a specific region and biorefinery location to determine the least-cost quantity and location of land to lease. They used biophysical model [24, 25] and historical weather data to simulate switchgrass yields for each of three land capability classes for each of 30 counties in their case study region for each of 50 years. The model was used to determine how the optimal quantity and location of land to optimally lease would change if they assumed that the average yield was obtained in each of the 50 years versus an assumption that sufficient land should be leased so that biorefinery feedstock requirements would be fully satisfied even in the worst case year (based on historical weather data). However, Debnath et al. [23] did not evaluate the opportunity cost of idling the plant due to insufficient feedstock. They did not consider the economic tradeoff between the cost of leasing sufficient land to insure adequate feedstock production in every year versus the cost of leasing less land and incurring the cost in some years of a forced idling of the biorefinery (downtime cost) due to insufficient feedstock.

The present research study builds on and extends the work of Debnath et al. [23] to further address the consequences of switchgrass yield variability. The objective is to determine for a given biorefinery location the least-cost quantity, quality, and location of land to lease for alternative estimates of biorefinery downtime cost due to variable switchgrass yields produced on leased land. Two models are developed. One does not permit storage across feedstock production seasons. The second model includes the option to store across seasons. Both models are presented and solved with switchgrass biomass yield data simulated from 50 years of weather data for the case study region. The models are used to determine the optimal number of idle

days, and the optimal quantity, quality, and location of land to lease, as a function of the biorefinery downtime cost. Findings from the two models can be compared to determine the expected economic consequences of switchgrass biomass storage across feedstock production seasons.

2. Mathematical Programming Models

An innovative model is developed for a given biorefinery location that enables determination of the optimal quantity, quality, and location of land to lease (L) considering yield variability, for a given level of biorefinery downtime (D) opportunity cost. The estimate of the opportunity cost of downtime may be parameterized to trace out the DL frontier; that is the Downtime Cost-Land to Lease frontier. A second model that enables year-to-year storage along with the downtime is also formulated. Findings from the DL frontier model may be compared to findings from the year-to-year storage model to determine the circumstances for which using storage across years would be warranted. The two models encompass both spatial (across land class and across counties within each year) and temporal (across years) biomass yield variability.

2.1. Model 1: Identifying the D (Downtime Cost) L (Land to Lease) Frontier

The model is designed to determine the economic tradeoffs between leasing less land than required to meet biomass needs in each production year resulting in some forced idle days in some years. The net cost of a forced idle day will depend on the lost revenue as well as on unavoidable production costs. However, this strategy could reduce the quantity and cost of land that is leased for switchgrass production. The objective function follows:

$$\min_{XL, XR, XB, XT, XS} EAS = \sum_i^I \sum_j^J \lambda_{ij} XL_{ij} + R \left(\sum_t^T \sum_i^I \sum_j^J XR_{tij} \right) / T + B \left(\sum_t^T \sum_i^I \sum_j^J XB_{tij} \right) / T + \left(\sum_t^T \sum_i^I \sum_j^J \tau_{ij} XT_{tij} \right) / T + D \left(\sum_t^T XS_t \right) / T \quad (1)$$

EAS includes the average costs across the T years of leasing land, producing, harvesting, and transporting biomass to the biorefinery, and the opportunity cost of biorefinery downtime for

those years during the T years when feedstock production on the leased land would be insufficient to meet biorefinery needs; λ_{ij} is the production cost (\$ ha⁻¹) including amortized establishment costs, land rent, fertilizer, and mowing costs in county i for land class j ; XL_{ij} is the quantity (ha) of land class j leased for switchgrass production in county i ; R is the cost (\$ ha⁻¹) to rake mowed biomass into a windrow for baling; XR_{tij} is the quantity (ha) of land class j raked in year t in county i ; B is the cost (\$ Mg⁻¹) of baling and stacking switchgrass biomass; XB_{tij} is the quantity (Mg) of switchgrass baled and stacked in year t from land class j in county i and; τ_{ij} is the cost (\$ Mg⁻¹) of loading and transporting switchgrass biomass in year t from county i and land class j to the biorefinery; XT_{tij} is the quantity (Mg) of switchgrass biomass transported from county i and land class j to the biorefinery; D is the downtime cost (\$ Mg⁻¹) of not delivering sufficient feedstock to meet biorefinery requirements and XS_t is the quantity (Mg) of switchgrass less than the biorefinery capacity that is not available for processing in year t (shortage). The model includes the following constraints with equations.

Equation (1) is minimized subject to the following set of constraints.

$$XL_{ij} \leq \sigma_{ij} \quad \forall i, j \quad (2)$$

Equation (2) imposes land constraints where σ_{ij} is the quantity (ha) of land class j in county i available for leasing from current use for conversion to switchgrass production, which is assumed to be 10% of the total available land in each class and in each county [23]. We further assumed that the conversion of 10% of land to switchgrass would not have negative environmental consequences relative to prior use.

$$XR_{tij} \leq XL_{ij} \quad \forall i, j \quad (3)$$

Equation (3) restricts the area (ha) raked to be less than or equal to the area leased. In a given year, only the quantity of biomass required to fulfill the needs of the biorefinery will optimally be raked. The area raked may differ in each state of nature.

$$XB_{ij} \leq \alpha_{ij} XR_{ij} \quad \forall t, i, j \quad (4)$$

Equation (4) restricts the quantity to be baled in year t from land class j in county i to be no more than the yield (α_{ij}) in year t from land class j in county i times the area raked.

$$XT_{ij} \leq XB_{ij} \quad \forall t, i, j \quad (5)$$

Equation (5) balances the quantity baled with the quantity transported to the biorefinery from land class j in county i for each year t .

$$\sum_i \sum_j XT_{ij} \geq \delta - XS_t \quad \forall t \quad (6)$$

For a given state of nature, equation (6) permits the annual biorefinery capacity (δ) to be relaxed by the quantity XS_t (Mg).

$$\sum_t XS_t \leq \eta \quad (7)$$

The total shortage quantity (Mg) across all years that may be permitted is constrained to a level η , as shown in equation (7). If the value of η , is set equal to zero, the model will identify sufficient land to be contracted to deliver δ Mg of feedstock in every year. To allow for average feedstock shortages that would result in one shutdown day per year, the value of η may be set equal to one times the daily capacity times the number of years that make up the empirical switchgrass yield distributions. The value of η may be changed in combination with the value of D in equation (1) to trace out the tradeoff between the cost to idle the biorefinery and the land area to lease; the cost-efficient D (Downtime cost) L (Land to lease) frontier.

$$\sum_i \sum_j \alpha_{ij} XR_{ij} + XS_t - XE_t = \delta \quad \forall t \quad (8)$$

Equation (8) balances the biomass production for each year. In years when production exceeds biorefinery requirements, XE_t tracks the quantity (Mg) of excess production and will be greater than zero. In years when production is short of biorefinery requirements, XS_t tracks the shortage quantity (Mg) and will be greater than zero.

$$XL_{ij}, XR_{ij}, XB_{ij}, XT_{ij}, XS_t, XE_t \geq 0 \quad (9)$$

Equation (9) restricts the choice variables to be nonnegative.

2.2. Model 2: Incorporating Interyear Storage

The model is designed to determine the economic tradeoffs that result from leasing less land resulting in some forced idle days in some years in the presence of storage capacity (XC_{ij}).

The objective function follows:

$$\min_{XL, XR, XB, XT, XS, XC} EAC = \sum_i \sum_j \lambda_{ij} XL_{ij} + R \left(\sum_t \sum_i \sum_j XR_{ij} \right) / T + B \left(\sum_t \sum_i \sum_j XB_{ij} \right) / T + \left(\sum_t \sum_i \sum_j \tau_{ij} XT_{ij} \right) / T + D \left(\sum_t XS_t \right) / T + S \left(\sum_t \sum_i \sum_j XC_{ij} \right) / T \quad (10)$$

EAC includes the expected annual cost (\$) of not meeting the biorefinery demand as well as the average costs per year of leasing land, producing, harvesting, storing and transporting biomass to the biorefinery; XC_{ij} is the quantity (Mg) of switchgrass storage capacity in year t in county i produced on land class j ; and S is the cost to store a Mg of switchgrass for one year. Other variables are as previously defined. Equation 10 is optimized subject to equations 2, 3, 4, 6, 11, 12, and 13. Equation 11 restricts the quantity to be stored in year t from land class j in county i to be no more than the quantity to be baled in year t from land class j in county i .

$$XC_{ij} \leq XB_{ij} \quad \forall t, i, j \quad (11)$$

Equation (12) balances the quantity baled in period t plus the quantity available in storage from prior periods after losing ϕ percentage of biomass in storage per year minus quantity transported to the biorefinery in period t with the quantity stored for use in period $t+1$.

$$XC_{t+1ij} = XB_{tij} + (1 - \phi)XC_{tij} - XT_{tij} \quad \forall t, i, j \quad (12)$$

Equation (13) includes the non-negativity constraints.

$$XL_{ij}, XR_{ij}, XB_{tij}, XT_{tij}, XS_t, XC_{tij} \geq 0 \quad (13)$$

3. Data and Study Region

A number of sources were used to obtain parameter values required by the models. A biorefinery was assumed to be located near Okemah in Okfuskee County, Oklahoma (Figure 1). Based on estimates provided by Kazi et al. [18] and Wright et al. [26], the biorefinery daily requirement of feedstock was set equal to 2 Gg. Assuming downtime required for maintenance and allowing for 350 days of operation per year, the annual feedstock requirement (δ) was set at 700 Gg.

Production practices budgeted to estimate the cost of switchgrass establishment, maintenance, and harvest, were based on a no-till establishment system [27]. Switchgrass was assumed to be seeded, but not harvested, in year one. The switchgrass biomass is assumed to be harvested (baled) once per year from year two onwards [23, 28, 29].

The quantity of available land with soil capability ratings of class I, II, and III in each county was determined from the USDA NRCS Land Survey Geographic (SSURGO) database [30]. 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 quantity of land (XL_{ij}) assumed to be available for leasing by the biorefinery was set equal to 10% of the total quantity of each land class in each county. In the 30 county study region 9% of

the class I-III land is class I, 28% is class II, and 63% is class III. The United States Department of Agriculture [31] cash rental rate which is a market based estimate of the opportunity cost of land was used as the land rental cost. The estimated land cost for each land class (I, II, and III) for each county was obtained by extrapolating the USDA cropland rental values using equation (14). Land rent cost for each land class in each county was estimated to be:

$$\omega_{ij} = \mu_{ij} \left(\frac{\sum_j X_{ij} \chi_i}{\sum_j \mu_{ij} X_{ij}} \right) \quad (14)$$

where, ω_{ij} is the rental cost of a hectare of land in county i and land class j ; μ_{ij} is the productivity rated wheat yield in county i and land class j as reported in the SSURGO data base, and; X_{ij} is the available hectares of land in county i and land class j ; χ_i is the USDA reported cropland rental rate for the county i .

Transportation costs (τ_{ij}) were calculated based on an equation modified from data reported by Wang [32]. Road distance between the town corresponding to the centroid of each land class and the biorefinery was obtained from Google maps (maps.google.com).

3.1. *Estimating Switchgrass Biomass Yield Distributions*

Switchgrass historical yields are not available. However, a proxy for historical yields may be simulated by a calibrated and validated biophysical plant growth simulation model if field trial yield data and historical weather data are available. The Environmental Policy Integrated Climate (EPIC) model [28, 29] was calibrated for switchgrass yields using EPIC v 0509 and validated against switchgrass biomass field trial yield data obtained from three locations in the region: Chickasha, Haskell, and Stillwater [33, 34]. 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 were conducted. Soil related

information for these land types including bulk density, water, clay, sand and silt content, organic carbon concentration, calcium carbonate content, saturated conductivity, and cation exchange capacity were obtained from the SSURGO land database [30]. Daily weather data of solar radiation, maximum temperature, minimum temperature, relative humidity, wind velocity, and precipitation for each of the three sites for each year for which data were available were obtained from the NOAA [35] and MESONET [36] weather data archives.

The calibrated EPIC model was used to simulate switchgrass biomass yields (α_{tij}) for 50 states of nature (1962-2011) ($t = 1, \dots, 50$) for three land classes (class I, II, and III) ($j = 1, \dots, 3$) for each of 30 counties ($i = 1, \dots, 30$). The soil classification within each land class 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. Historical weather data for each county were obtained from the NOAA [35] data base for years 1962 through 2011 and supplemented with data from local weather stations [36]. Thus, proxies for empirical yield distributions that contained 50 observations were produced for each county and each land class.

3.2 Cost of Idling the Biorefinery

The net amount of revenue lost due to not delivering a Mg of feedstock that could be processed will depend on the lost revenue as well as on the variable production costs that can be avoided. If it is assumed that none of the biorefinery operating costs can be avoided, lost revenue from not producing biofuel will depend on the net market price of biofuel. From January of 2010 through December of 2011 the Iowa weekly average ethanol price ranged from 0.38 \$ to 0.78 \$ L⁻¹ [37]. These prices were influenced to some extent by public policies that provided subsidies and mandates. Ethanol contains less energy than unleaded gasoline [38]. When relatively low

volumes of ethanol are blended with gasoline, 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 energy content results in a proportionately lower fuel economy. If direct subsidies for ethanol are eliminated, and if ethanol production exceeds the quantity required for ten percent blends, the marginal value of ethanol could be expected to be based on its energy content relative to gasoline. Based on the reference case for crude oil price for 2025 of 860 \$ Mg⁻¹, as projected by the U.S. Energy Information Administration [38], an ethanol price based on energy equivalence would be 0.50 \$ L⁻¹. For a conversion rate of 375 L Mg⁻¹, and a wholesale biofuel price of 0.50 \$ L⁻¹ the penalty charges for not processing feedstock derived from the lost revenue would be 187.50 \$ Mg⁻¹. This provides an estimate of the value of D in equation (1). Since some of the operating costs may be avoided if the biorefinery is idled, this can be interpreted as an upper bound estimate of the penalty for not processing one Mg of feedstock.

Results from the Debnath et al. [23] study were used to compute an upper value for the parameter η in equation (7). Based on their findings, if the biorefinery elected to contract for land based on average yields it would average 14.15 days per year of required idling due to insufficient feedstock. For a 2 Gg per day biorefinery this would be an average annual shortage of 28.3 Gg. This value can be multiplied by the number of states of nature in the yield data set (in this case $T = 50$) to obtain an upper value for η . The initial value of η was set at 1,420 Gg.

3.3. *Storage Cost and Storage Losses*

Cundiff and Marsh [39] estimated an annual storage cost of 14-16 \$ Mg⁻¹ y⁻¹ and 3% storage loss. Sanderson et al. [40] reported storage losses of 13% after six months of outside storage for unprotected round bales. Losses for bales stored inside were negligible. Larson et al.

[22] found storage dry matter losses of 30% for rectangular solid bales of switchgrass that were covered with a tarp and stored for 360 days. They estimated storage cost to be 6 \$ Mg⁻¹ y⁻¹ for tarp and pallet and 12 \$ Mg⁻¹ y⁻¹ for tarp and gravel. Turhollow et al. [41] estimated the cost of storing large rectangular solid bales on (a) the ground (unprotected), (b) a gravel pad with a tarp, and (c) inside a storage building to be 1.12 \$ Mg⁻¹ y⁻¹, 10.87 \$ Mg⁻¹ y⁻¹, and 25.20 \$ Mg⁻¹ y⁻¹. They estimated that annual storage losses would be 25%, 6%, and 2%, for systems (a), (b), and (c), respectively. They [41] also estimated the storage cost of 1.22 x 1.22 x 2.44 m rectangular bales with plastic wrap is 6.71 \$ Mg⁻¹ y⁻¹. Mohua et al. [12] assumed that in Oklahoma the cost associated with covering rectangular bales with plastic tarp was 2.20 \$ Mg⁻¹ y⁻¹ with a storage loss of 1% per month, that is, 12% annual storage loss. For the current study, baseline model 2 is estimated using storage costs of 6.71 \$ Mg⁻¹ y⁻¹ and storage loss of 12% per year. Further, three different scenarios are estimated for three levels of storage cost 6 \$ Mg⁻¹ y⁻¹, 12 \$ Mg⁻¹ y⁻¹, and 18 \$ Mg⁻¹ y⁻¹ and three levels of storage loss, 10, 20, and 30 % y⁻¹.

4. Results

The modeling exercise follows from the conceptual framework that a specific quantity of land will be removed from current use and seeded to switchgrass. In some years, the biomass production on the contracted land will exceed the quantity that can be processed in a year by the biorefinery. In other years, biomass production will not be sufficient to provide for the biorefinery to operate at full capacity. The results obtained from solving the optimization models without storage (model 1) and with storage (model 2) are described in the following subsections.

4.1. No Interyear Storage

For a given level of η the level of D was parameterized to determine the tradeoff between the cost of not processing a Mg of switchgrass and the optimal quantity of land to lease. Results are reported in table 1 and figure 2. For a biofuel price of 0.50 \$ L⁻¹ and a conversion rate of 375 L Mg⁻¹, every Mg not processed represents a lost opportunity to gain 187.50 \$ in revenue. For this situation, model 1 (without interyear storage) predicts the biorefinery would optimally lease 53,379 ha. This would result in an average of 2.97 days per year during which the biorefinery would be idled due to insufficient feedstock. The D (Downtime Cost) L (Land to Lease) frontier has been traced out in figure 2. As the downtime cost increases, the biorefinery optimally leases more land and reduces the expected downtime.

The average annual cost of leasing the land and producing, harvesting, and delivering the feedstock would be 43.1 M \$. The average annual opportunity cost of the lost revenue (downtime cost) from insufficient feedstock would be 1.1 M \$. Adding these two costs and dividing by the proposed hypothetical biorefinery annual requirement (700 Gg), results in a switchgrass feedstock price including the opportunity cost of idling the biorefinery of 63.10 \$ Mg⁻¹. This 53,379 ha can be compared to the 60,492 ha that would be required to insure that adequate feedstock be produced in every year to prevent downtime. The opportunity cost of closing the biorefinery would have to increase to 960 \$ Mg⁻¹ before it would be optimal to lease 60,492 ha that would be required to insure against a feedstock shortage shutdown.

4.2. Enabling Interyear Storage

For baseline estimated interyear storage cost of 6.71 \$ Mg⁻¹ y⁻¹, storage losses of 12% y⁻¹, and downtown (D) cost of 187.50 \$ Mg⁻¹ (based on a 0.50 \$ L⁻¹ biofuel price), model 2 selects 52,034 ha for leasing (table 2). Area leased by county and land class are reported in figure 3. In some years the 52,034 ha would produce more biomass than could be processed. In other years

production would be insufficient and biomass would be removed from storage to fulfill the biorefinery requirements. For purposes of modeling and to accommodate historical weather cycles, the 50 years of simulated yields were ordered based on the 1962 to 2011 historical weather. For the initial year, it is assumed that zero biomass is available from storage. For subsequent years, the model either places biomass in storage or removes biomass from storage depending on production. By this measure the average cost to deliver feedstock is estimated to be \$61.12 Mg^{-1} for the baseline assumptions.

To determine the value of enabling interyear storage, findings from model 2 may be compared to findings from model 1. Model 2 selects the same set of land for leasing as model 1 when the storage cost (baseline) is 6.71 \$ $\text{Mg}^{-1} \text{y}^{-1}$ and the storage loss is 80% y^{-1} and when the storage costs is 120 \$ $\text{Mg}^{-1} \text{y}^{-1}$ and the storage loss (baseline) is 12% y^{-1} (shown in table 2). Given the expected cost and expected storage losses from interyear storage, these findings suggest that enabling interyear storage is expected to result in lower average feedstock cost. Findings from solutions with alternative levels of storage loss and storage cost assumptions are reported in table 2. Figure 4 includes a chart of the cost to deliver switchgrass (including the opportunity costs of idling the biorefinery) without storage and with storage for several alternative levels of storage costs and storage losses.

With interyear storage loss of 10% y^{-1} and storage costs of 6, 12, or 18 \$ $\text{Mg}^{-1} \text{y}^{-1}$, it is optimal to lease sufficient area and to store biomass in years of excess production for use in years of less than average production and to not idle the biorefinery. The solution to model 2 finds that is optimal to idle the biorefinery an average of 0.2 d y^{-1} when the storage cost is 18 \$ $\text{Mg}^{-1} \text{y}^{-1}$ and storage loss is 20% y^{-1} . When storage cost is 6 \$ $\text{Mg}^{-1} \text{y}^{-1}$ and storage loss is 30% y^{-1}

it is optimal to lease 52,596 ha and the biorefinery would optimally be shut down an average of 0.38 (downtime) days per year (shown in table 2).

If the net cost of idling the biorefinery as a result of insufficient feedstock were 0.50 \$ L⁻¹, and storage was not permitted, then the estimated annual cost of downtime that would result from leasing the 53,379 ha would be 1.1 M \$ (table 3). The average annual cost of feedstock plus downtime cost would be 44.1 M \$ (table 3). If, on the other hand, the biorefinery elected to enable interyear storage with expected storage costs of 6 \$ Mg⁻¹ y⁻¹ and expected storage losses of 30% y⁻¹, the average annual cost of feedstock plus downtime would be 43.1 M \$. Enabling interyear storage reduces the forced downtime by 2.59 d y⁻¹ but also reduces the average cost of feedstock including the downtime by 1.02 M \$. The difference between these two values (1.02 M \$) is an estimate of the annual value of enabling interyear storage. Since the useful life of a biorefinery is expected to exceed 10 years, land contracts to produce feedstock could also be expected to be for at least 10 years, similar to 10-15 year CRP land contracts [4]. Table 3, also includes estimates of the present value of permitting interyear storage (model 2) relative to not permitting storage (model 1). For a 10-year contract and a discount rate of 10% the present value of enabling interyear storage while considering spatial and temporal yield variability when selecting land to lease for a single 2 Gg d⁻¹ biorefinery in the region would exceed 6.2 M \$ (table 3). Based on the findings summarized in table 3, for the study region, a strategy to store excess production for use in later years of less than average production would be preferable to a no storage strategy.

5. Discussion

Several researchers have posited that cost reductions are expected to be achievable with the nth relative to the first cellulosic biorefinery with a specific technology [18, 26]. However,

these analyses have failed to consider that unlike corn ethanol plants that can procure a flow of feedstock by simply offering a price premium for corn grain relative to the local elevator, each cellulosic biorefinery designed to process a dedicated perennial energy crop such as switchgrass, will need to pay careful attention to feedstock procurement. Transportation costs can be expected to limit the procurement region for a biorefinery. Biomass yield from perennial grasses varies considerably across regions and across years [23, 42]. Based on the findings presented for the region evaluated, failure to consider spatial and temporal yield variability could be quite costly. If the initial biorefineries locate in regions with less biomass yield variability, the n^{th} biorefinery may be located in a region with more yield variability and greater feedstock cost. The modeling system presented herein is generalizable to other regions and to other perennial dedicated energy crops. The value of strategically selecting land to contract will vary across regions and across species.

In the absence of government imposed distortions, a cost-efficient switchgrass feedstock biorefinery system could engage in long term contracts with land owners to lease a sufficient quantity of land to provide for feedstock needs prior to, or simultaneously with, construction of a biorefinery. Land could be leased in a manner similar to what occurred when millions of hectares were converted from cropland and enrolled in the CRP. The difference being that the biorefinery rather than the government would be the lessee and would be responsible for paying the leasing cost. The CRP was established in 1985. USDA provided CRP participants with an annual rent and half the cost of establishing a permanent land cover (usually grass or trees) in exchange for 10 or 15 year leases. During the first three enrollment periods in 1986, more than three million hectares were contracted. Within two years after the 1985 legislation, nine million U.S. hectares were under contract [4]. This history suggests that if an economically competitive biorefinery

technology is developed, entrepreneurs could prepare a field-to-fuel business model and contract and convert millions of hectares from current use to the production of a perennial dedicated energy crop in a relatively short period of time.

Companies may be reluctant to contract for sufficient quantities of land to provide for feedstock needs. Public opinion may not support conversion of 50,000 ha in a region from existing use to the production of a dedicated energy crop. The probability of successful rent seeking behavior on behalf of the biorefinery may be reduced if it becomes clear that production of perennial grass feedstock is more akin to harvesting CRP lands than farming conventional annual crops. Public officials may place impediments limiting the ability of biorefineries to lease large tracts of land. However, ambiguities as to what determines feedstock quality and how to provide a flow of feedstock throughout the year are likely to be resolved much more quickly if the annual payment to the land owner is set. Leased land would enable the biorefinery to manage feedstock quality and to manage harvest and transportation to optimize the field to biofuel system.

A producer owned cooperative is an alternative type of business organization that could also be used to facilitate switchgrass biomass production. In the USA, a business plan for a switchgrass biomass biorefinery could be formulated as a closed-membership producer cooperative. The cooperative could build and manage the biorefinery as is the case with some corn ethanol plants in the USA Corn Belt. The cooperative would require a predetermined capital investment and pledges of switchgrass biomass from its members [14, 43]. The cooperative could contract biomass delivery terms with members. The contract between members and the cooperative would obligate members to deliver biomass from a specified number of hectares over a specified number of years.

A third alternative would be to separate the biomass production business from the biomass processing business. For example, a cooperative could be formed to produce, harvest, and deliver feedstock. The cooperative could then contract with a biorefinery to provide a flow of feedstock throughout the year. This would enable the cooperative to specialize in switchgrass biomass production and the biorefinery to specialize in processing, and disperse the risk across the business entities.

The most economical method for insuring a flow of biomass for the life of a cellulosic biorefinery remains to be determined. Potential investors could be expected to require that the proposed biorefinery have a reasonable plan for acquiring a steady flow of feedstock day-after-day, year-after-year, for its expected life. Switchgrass yields vary across time and space. The models developed and presented in this paper may be used to identify for a specific region the optimal quantity and quality of land to convert from current use to switchgrass production, in light of expected yield variability, and the opportunity cost of idling the biorefinery.

6. Conclusion

An innovative mathematical programming model was developed and used to reveal the cost-efficient D (Downtime Cost) L (Land to Lease) frontier for a 2 Gg d⁻¹ switchgrass biomass capacity biorefinery. For the case study region, and the simulated yield distributions based on 50 years of historical weather, if interyear storage is not permitted, 60,492 ha would be required to insure that the biorefinery run at full capacity every year. However, for some circumstances, it would be optimal to produce switchgrass on only 49,464 ha and idle the biorefinery for some days in low biomass production years. For the region, a strategy to store excess production for use in later years of less than average production is preferable to a no storage strategy. For storage costs ranging from 6 \$ to 18 \$ Mg⁻¹ y⁻¹ and interyear storage losses ranging from 10% to

30% y^{-1} , the optimal quantity of land to lease ranges from 51,818 to 52,705 ha and estimated cost to deliver biomass ranges from 61.02 to 62.00 \$ Mg^{-1} . For the case study region and baseline assumptions, the present value of enabling interyear storage for the 700 $Gg\ y^{-1}$ biorefinery exceeds 6.2 M \$.

Acknowledgments

The authors would like to thanks the editor Dr. R. Overend and the three anonymous reviewers for their thoughtful comments and suggestions that help us to improve this research paper. Funding for this project was provided by the USDA-NIFA, USDA-DOE Biomass Research and Development Initiative, Grant No. 2009-10006-06070, by the USDA National Institute of Food and Agriculture, Hatch grant number H-2824; the Jean & Patsy Neustadt Chair; and by the Oklahoma Agricultural Experiment Station. Support does not constitute an endorsement of the findings expressed.

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Table 1. Biofuel price, corresponding revenue lost in the event of insufficient biomass, the number of days in an average year the biorefinery is forced to be idle, average cost to deliver switchgrass, and quantity of leased land without considering storage.

Net Biofuel Price (\$ L ⁻¹)	Downtime Cost (<i>D</i>) (\$ Mg ⁻¹ not processed) ^a	Forced downtime (average d y ⁻¹)	Land Leased (<i>L</i>) (ha)	Average Annual Shortage (Mg) ^b	Average Annual Delivered Feedstock (Mg)	Annual Cost of Forced Downtime (\$ y ⁻¹)	Annual Cost of Delivering Feedstock (\$ y ⁻¹)	Switchgrass Delivered Cost (\$ Mg ⁻¹) ^c
$\eta = 1,420,000^b$								
0.10	37.50	14.15	49,464	28,306	671,694	1,061,475	40,511,170	59.39
0.20	75.00	14.15	49,464	28,306	671,694	2,122,950	40,511,170	60.91
0.30	112.5	6.86	51,465	13,727	686,273	1,544,288	41,953,190	62.14
0.40	150.00	4.24	52,198	8,488	691,512	1,273,200	42,611,090	62.69
0.50	187.50	2.97	53,379	5,937	694,063	1,113,209	43,057,150	63.10
0.60	225.00	1.94	54,212	3,879	696,122	872,775	43,470,000	63.35
1.20	450.00	0.32	55,813	631	699,369	283,950	44,445,260	63.90
2.56	960.00	0	60,492	0	700,000	0	44,919,930	64.17
$\eta = 1,000,000$								
0.10	37.50	10	51,092	20,000	680,000	750,000	41,287,740	60.05
0.20	75.00	10	51,092	20,000	680,000	1,500,000	41,287,740	61.13
0.30	112.50	6.86	51,465	13,727	686,273	1,544,288	41,953,190	62.14
$\eta = 500,000$								
0.10	37.50	5.00	51,923	10,000	690,000	375,000	42,402,630	61.11
0.20	75.00	5.00	51,923	10,000	690,000	375,000	42,402,630	61.11
0.30	112.50	5.00	51,923	10,000	690,000	375,000	42,402,630	61.11
0.40	150.00	4.24	52,198	8,488	691,512	1,273,200	42,611,090	62.69

^a Here *D* from model 1 (equation 1) is assumed to be equal to the lost sales revenue from not processing as a result of insufficient feedstock.

^b Constraint equation (7) from model 1 limits total biomass shortage across all years to a level, η . The average annual shortage is η/T . The initial level of η was set equal to the average shortage per year as computed by average yield model [23] times *T*.

^c The downtime (opportunity) costs of idle days faced by the biorefinery due to insufficient feedstock is included in the estimated cost to deliver a flow of switchgrass.

Table 2. Different levels of biomass storage costs and storage loss and corresponding biofuel price, revenue lost for not processing switchgrass feedstock, the number of days in an average year the biorefinery is forced to be idle, average cost to deliver switchgrass, and quantity of leased land.

Storage Costs (\$ Mg ⁻¹ y ⁻¹)	Forced downtime (avg. d y ⁻¹)	Land Leased (ha)	Average Annual Shortage (Mg) ^a	Average Annual Delivered Feedstock (Mg)	Average Annual Stored Feedstock (Mg)	Average Annual cost of Forced Downtime (\$ y ⁻¹)	Average Annual Cost of Delivering Feedstock (\$ y ⁻¹)	Average Annual Cost of Storage (\$ y ⁻¹)	Switchgrass Delivered Cost ^b (\$ Mg ⁻¹)
Storage loss= 10%									
6.00	0	51,818	0	700,000	31,071	0	42,711,490	186,430	61.02
12.00	0	52,289	0	700,000	23,054	0	42,892,560	276,644	61.28
18.00	0	52,427	0	700,000	18,671	0	43,039,010	336,084	61.48
Storage loss= 12%									
6.71	0	52,034	0	700,000	28,287	0	42,782,180	189,806	61.12
120.00	2.97	53,379	5,937	694,063	0	1,113,209	43,057,150	0	63.10
Storage loss= 20%									
6.00	0	52,665	0	700,000	22,225	0	42,932,970	133,352	61.33
12.00	0	52,705	0	700,000	19,230	0	43,084,400	230,763	61.55
18.00	0.20	52,575	395	699,605	16,787	74,050	43,140,190	302,168	61.74
Storage loss= 30%									
6.00	0.38	52,596	760	699,240	15,339	142,440	43,005,040	92,034	61.64
12.00	0.50	52,539	1,019	698,981	14,094	190,999	43,086,300	169,126	61.83
18.00	0.51	52,462	1,021	698,979	12,848	191,379	43,200,900	231,261	62.00
Storage loss= 80%									
6.71	2.97	53,379	5,937	694,063	0	1,113,209	43,057,150	0	63.10
120.00	2.97	53,379	5,937	694,063	0	1,113,209	43,057,150	0	63.10

^a D from model 2 (equation 10) is assumed to be equal 187.50 \$ Mg⁻¹ with the assumption of 0.50 \$ L⁻¹ of biofuel price.

^b Switchgrass delivered cost includes the downtime (opportunity) costs of idle days faced by the biorefinery due to insufficient feedstock.

Table 3. Estimated value of strategically selecting land to lease with year-to-year storage if the net cost of failure to deliver feedstock is \$187.50 Mg⁻¹ (biofuel price of \$0.50 L⁻¹) over switchgrass feedstock operation without storage.

Forced downtime (avg. d y ⁻¹)	Land Leased (ha)	Average Annual Shortage (Mg)	Average Annual Delivered Feedstock (Mg)	Estimated Annual cost of Forced Downtime (\$ y ⁻¹)	Annual Cost of Delivering Feedstock (\$ y ⁻¹)	Average Annual Cost of Feedstock Plus Downtime (\$ y ⁻¹)
Model 1 ^a						
2.97	53,379	5,937	694,063	1,113,209	43,057,150	44,170,359
Model 2 ^b						
0.38	52,665	760	699,240	142,440	43,005,040	43,147,480
Model 1 minus Model 2 value						
2.59	714	5,177	-5,177	970,769	52,110	1,022,879
Present value of permitting interyear storage						
		Discount Rate	Lease Length (y)		Present Value ^c	
		0.1	10		\$6,285,149	
		0.1	15		\$7,780,099	
		0.15	10		\$5,133,593	
		0.15	15		\$5,981,152	

^a Model 1 is based on the assumption of zero year-to-year storage.

^b Model 2 permits year-to-year storage. These findings are based on a budgeted storage cost of 6 \$ Mg⁻¹ y⁻¹ and an estimated storage loss of 30% per year.

^c Present value of the difference (1.02 M \$) between the average annual cost of feedstock plus downtime obtained from model 1 (44.2 M \$) and model 2 (43.1 M \$) for noted discount rate and lease length.

Figure 1. Map showing the 30 Oklahoma counties included in the models for potential switchgrass production.

Figure 2. D (Downtime Cost) L (Land to Lease) frontier.

Note: Tradeoff between leasing more land versus the biorefinery's forced downtime due to insufficient feedstock under model 1, without storage, and model 2, with storage. For model 2, storage costs and storage loss is assumed to be 6 \$ Mg⁻¹ y⁻¹ and 30% y⁻¹, respectively.

Figure 3. Optimal hectares of land class I (CLS I), land class II (CLS II), and land class III (CLS III) leased in counties surrounding the hypothetical biorefinery located in Okemah, Oklahoma, USA under different scenarios: (i) model 1: without year-to-year storage, and (ii) model 2: with year-to-year storage.

Figure 4. Cost to deliver a flow of switchgrass to the biorefinery (\$ Mg⁻¹) including the opportunity costs of idling the plant under different scenarios.

Note: Five different scenarios are: (i) without year-to-year storage, (ii) storage costs of 6.71 \$ Mg⁻¹ y⁻¹ and 12% storage loss per year, (iii) storage costs of 18 \$ Mg⁻¹ y⁻¹ and 10% storage loss per year, (iv) storage costs of 12 \$ Mg⁻¹ and 20% storage loss per year and (v) storage costs of 6 \$ Mg⁻¹ y⁻¹ and 30% storage loss per year, assuming $D = 187.50$ \$ Mg⁻¹.