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Economic analysis of delivering switchgrass to a biorefinery from both the farmers' and processor's perspectives

Chenguang Wang
University of Tennessee

To the Graduate Council:

I am submitting herewith a thesis written by Chenguang Wang entitled "Economic analysis of delivering switchgrass to a biorefinery from both the farmers' and processor's perspectives." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Economics.

James A. Larson, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Burton C. English

Kimberly L. Jensen

Accepted for the Council:

Carolyn R. Hodges, Vice Provost and
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(Original signatures are on file with official student records.)

ECONOMIC ANALYSIS OF DELIVERING SWITCHGRASS TO A BIOREFINERY FROM BOTH THE FARMERS' AND PROCESSOR'S PERSPECTIVES

A Thesis
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Master of Science
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Chenguang Wang
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ABSTRACT

Switchgrass for bioenergy production will require substantial storage. The first paper evaluates costs of various baling and on-farm storage systems by simulating the final delivered costs to the biorefinery under two representative soil types in East Tennessee and West Tennessee. Influences of the volatilities of switchgrass yield, diesel fuel price and nitrogen fertilizer price on delivered costs are considered. Results show that rectangular bales minimize cost if switchgrass is processed immediately after harvest. However, round bales minimize cost if switchgrass is stored without protection for 200 days before being transported to the biorefinery.

The second paper evaluates from the processors' perspective the least cost delivery schedule for switchgrass to a biorefinery considering bale types and storage methods. A mixed integer programming model was used to optimize the year round switchgrass delivery schedule within 50 miles of the biorefinery in East Tennessee from the processors' perspective, while minimizing the annual costs of delivering switchgrass. The delivery is constrained by land availability, switchgrass yields, field days for harvest, and storage dry matter loss. Scenario analyses for different plant sizes, harvesting systems, existence of storage loss and equipment efficiency were done in this study. Results from the base model show that the delivered cost, which accounts for $0.73/gallon of ethanol produced, is almost twice the U.S. Department of Energy's National Renewable Energy Laboratory's goal for feedstock production in 2012.

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Part 1: Cost Analysis of Alternative Harvest, Storage and Transportation Methods for Delivering Switchgrass to a Biorefinery from the Farmers' perspective

INTRODUCTION

The U.S. government has mandated the development of renewable substitutes for oil to reduce the reliance on imported oil and mitigate the environmental degradation caused by fossil fuels (Thorsell et al. 2004). In addition, the petroleum derived additive methyl tertiary-butyl ether (MTBE) which has been used as an oxygenate in gasoline has been proposed to be banned nationwide in 2009 because of the potential negative impacts of MTBE on the environment and human health (Keller et al. 1998). In 2005, the Environmental Policy Act of 2005 required more ethanol production by 2012. Ethanol, as a fuel oxygenate, has become a potential attractive substitute for petroleum oil. According to the Industrial Statistics, between 1996 and 2006 in the United States, fuel ethanol production rose from 1.770 to 4.855 billion gallons (Renewable Fuels Association 2008). The increased production of ethanol was fueled by a rapid expansion in demand for substitutes for MTBE and by a 51 cent per gallon blended credit provided by the U.S. government. The total quantity demanded for fuel ethanol doubled to 5.377 billions of gallons in 2006 compared with the number in 2002 (Renewable Fuels Association 2008). The growth rate of demand for ethanol is greater than the growth rate in supply. As a result of this excess demand for fuel ethanol, the price of ethanol has increased. One possible efficient method to curb the increase in the ethanol price is to increase supply by decreasing the cost of ethanol production.

Traditionally, corn grain has been used in ethanol production. Compared with the price received for ethanol, however, the cost of ethanol production with corn grain is high, making corn grain based ethanol production less attractive (Mapemba and Epplin 2004). Tembo, Epplin and Huhnke (2003), suggested that crops with high cellulose are more efficient materials than corn grain in ethanol production. Lignocellulosic Biomass (LCB) is composed of cellulose, hemicellulose and lignin. The cellulos and hemicellulose can be converted to sugar for ethanol production and the lignin can be burned for electricity (Wyman 2008). For example, corn stover, wheat straw and some dedicated energy crops such as switchgrass (*Panicum virgatum*) are considered potential materials for ethanol production. The Energy Independence and Security Act of 2007 have mandated that 36 billion gallons per year of ethanol be produced in the U.S. by 2022, with 21 billion gallons per year from feedstocks other than corn (U.S. Congress 2007). The production of LCB feedstocks such as switchgrass will be needed to meet the aggressive goals mandated by Congress (De La Torre Ugarte, English and Jensen. 2007).

Switchgrass, a warm season perennial grass native to the United States, is widely recognized as a potential leading crop for energy production (McLaughlin 2002). Switchgrass is a hardy, drought resistant plant that can grow in a variety of soils. It has the potential to open up new markets for farmers since it can grow on marginal agricultural lands that may be unsuitable for other crops (Tiller 2008). Due to the large amount of marginal crop lands in Tennessee, the State is not an ideal location for the production of row crops such as corn and cotton because of concerns about soil erosion and nutrient runoff. However, abundant sunshine and rainfall make Tennessee competitive to other states on the production of grasses such as switchgrass.

Notwithstanding the potential of switchgrass as an energy feedstock, switchgrass is a bulky material relative to the energy contained, so it is relatively expensive to harvest, store, and transport and thus are essential determinants of the cost of ethanol derived from switchgrass. A number of researchers have evaluated the economic feasibility of using LCB for bioenergy and bioproduct production including McCarl, Adams and Alig (2000), Dipardo (2001), Haq (2001), Bernow et al. (2002), and English et al. (2004). In addition, numerous studies have estimated the cost of producing energy crops in the U.S. including Downing (1996), Duffy and Nanhou (2001), Graham (1995), Johnson and Baugsund (1990), Lindsey and Volk(1998), Mooney et al. (2008), Perrin et al. (2008), Vadas et al. (2008), Vaughan (1989), and Walsh et al.(1998).

Less well understood is how the emerging industry of interrelated feedstock producers, bio-refineries, and auxiliary service providers, such as transportation and storage, will be structured and how each will bear and/or share costs and risks. Analyses by Bhat et al. (1992), Cundiff (1996), Cundiff and Marsh (1996), Cundiff et al. (1997), Epplin (1996), Thorsell et al. (2004), Bransby et al. (2005), Sokhansanj et al. (2006), Mapemba et al. (2007), Kumar and Sokhansanj (2007), and Popp and Hogan (2007) have evaluated some of the aspects of the costs and risks of harvest, storage, and transportation of biomass feedstocks but not under Tennessee growing conditions.

There are a number of on-farm issues related to the harvest, storage, and transportation of switchgrass in Tennessee. The projected harvesting time for switchgrass is once in the fall after a killing freeze (Rinehart 2006). After a freeze, nutrients move into the root system, minimizing the harvest of nutrients and their replacement, and maximizing the lignocellulosic material for conversion to ethanol. Switchgass can be harvested using conventional hay equipment. However, the coarse and fibrous switchgrass harvested after a killing freeze may increase repair and maintenance costs of equipment and reduce the lifespan of equipment compared with other forage-type materials. Reported yields of switchgrass vary between 1 and 16 tons per acre (Rinehart 2006). With the large amount of biomass to be harvested, machine and labor time per unit of crop area will likely increase for each additional ton harvested, thus machinery and labor costs per acre will likely be higher for switchgrass (Cundiff 1996). In addition, the costs of production might dramatically differ among the alternative harvest and storage methods that could be used for switchgrass production in Tennessee. Currently, there is a lack of information about the cost of different switchgrass harvest and storage methods under Tennessee conditions.

Another important factor that might influence biomass production costs is weather in Tennessee. Higher precipitation in the fall and winter months may limit field days and increase harvest times and biomass losses relative to other potential harvest periods (Hwang and Epplin 2007). Moreover, the once-a-year harvest, coupled with the daily need for feedstock at the bio-refinery, will likely require storage of a substantial amount of biomass away from the plant on the farm. Precipitation and weathering may affect the quality and dry matter losses of bales delivered to the plant and thus the yield of ethanol from a ton of switchgrass (Wiselogel et al. 1996). In addition, the weight of bales transported to the bio-refinery may be influenced by the level of exposure to precipitation while being stored on the farm. Uncovered on-farm storage may increase transportation costs to the bio-refinery as well, especially in areas that have high precipitation such as in Tennessee. Thus, a processor may require that stored bales be protected from precipitation and weathering. However, large numbers of dry switchgrass bales under storage may be a fire hazard and present liability issues for the farmer.

Given the aforementioned issues, research is needed to evaluate the tradeoffs of different on-farm harvest and storage methods and arrangements under typical farm resources, farm constraints, and weather conditions in Tennessee. Research about switchgrass production costs under different harvest and storage systems and weather will provide farmers, potential processors, and other decision makers with information to make least-cost and risk minimizing choices with regard to biomass crop production.

Early research has been focused on switchgrass production and ethanol conversion in biorefinery. Epplin (1996) estimated the costs of establishing switchgrass on cropland and maintaining and harvesting an established stand in Oklahoma. Mapemba et al. (2007) studied the influence of policies on switchgrass production on Conservation Reserve Program (CRP) land. Tembo, Epplin and Huhnke (2003) identified specific regions, timing, biorefinery size for the conversion of switchgrass. Phillips et al. (1994) invented the gasification-fermentation system in which LCB can be converted to ethanol. Mapemba and Epplin (2004) examined how the accounting method used in determining the LCB harvest costs changes the estimated cost in the production of ethanol.

Research on logistics of switchgrass can be classified into three categories: traditional enterprise budgeting analysis, linear programming optimization and simulation analysis. Based on a 3.64 dt/acre yield, Epplin (1996) estimated the cost for annual stand maintenance and harvesting to be $12.30/dt and cost for loading and transportation was estimated to be $12.18/dt. Gallagher et al. (2003) examined the cost and supply for various crop residues. Thorsell et al. (2004) specified the least cost set of machines for harvest and estimated the supply of biomasses for different biorefinery capacities. Bransby et al. (2005) used a switchgrass budget model to determine whether the harvest material was baled, chopped, modulized or pelleted in some scenarios. Popp and Hogan (2007) adopted two alternative harvesting and transportation methods (round bale and module harvested) that may be suitable for Arkansas conditions. The use of labor, storage protection (bale wrap and tarps), equipment intensity and final product (chopped or merely conditioned) were differentiated in these two systems.

Besides the enterprise budgeting, some researchers chose linear programming to optimize the harvest, transport and storage process. Cundiff, Dias and Sherali (1997) estimated the schedules for shipping biomass from farmers' storage facilities to the central plant under weather uncertainty. Tembo, Epplin and Huhnke (2003) determined the regions which are the most economically suitable for Oklahoma, timing of harvest and storage, inventory management, biorefinery size and location as well as the breakeven price of ethanol by their mixed integer model. Kumar, Sokhansanj and Flynn (2006) developed a multi-criteria assessment model to rank alternative systems for biomass collection and transportation. Either traditional enterprise budgeting or the linear programming method does a good job for scenario and sensitivity analysis.

In recent years, more and more research has been done by simulation analysis on the logistics of switchgrass. Lowenberg, DeBoer and Cherney (1989) simulated the yield, cost and return of switchgrass based on several crucial factors such as weather, fertilizer and time. Cundiff (1996) found that the harvest and transportation of switchgrass is an equipment-intensive enterprise, accounting for two-thirds of the total cost, while the production accounts for one-third. Cundiff and Marsh (1996) compared harvest and on-farm storage costs for large round bales and rectangular bales. At the 3.64 dt/acre yield, harvest costs were \$19.06/dt and \$14.68/dt for round bale and rectangular bale. However, the storage costs were \$3.83/dt and \$16.97/dt for round bale and rectangular bale respectively. They found that the difference in cost becomes less significant, when the yield is above 3.64 dt/acre and storage losses for round bales stored outside increase above 5 percent. Nilsson (1999, 2000) analyzed factors that influence the performance and costs for delivering wheat straw to several heating plants in Sweden using a simulation model. The most influential factors affected costs were frequency and duration of rainfall. The simulation model incorporated the cost of infrastructure and field weather conditions as well. Sokhansanj, Kumar and Turhollow (2006) developed an Integrated Biomass Supply and Logistics (IBSAL) model to simulate the switchgrass collection, storage, transport and pre-processing. Sokhansanj, Eng and Fenton (2006), used the IBSAL model and found that the most important factors that affect the total delivery cost are the bulk density of biomass, moisture content and the distance to be transported. Kumar and Sokhansanj (2007) estimated the cost, energy input and carbon emissions by using the IBSAL model. However, none of them studied how variabiliiesy in switchgrass yield, storage dry matter losses, and input prices impact the distribution of per dry ton cost of delivering switchgrass to a biorefinery.

Research Objectives

1. To ascertain the costs of establishment, maintenance, alternative farm-level harvest, storage and transportation methods for switchgrass considering typical farm resources, farm constraints, and weather conditions in East Tennessee.
2. To determine the draw areas and optimal delivery schedule that result in the least delivered cost to the biorefinery considering typical farm and biorefinery constraints and weather conditions in East Tennessee.

This study assumed that farmers are paid for the amount of switchgrass that is delivered to the biorefinery less dry matter losses during storage. Farmers must take all the measurable inputs costs to deliver switchgrass into consideration. The inputs costs mainly include costs for switchgrass stand establishment, annual maintenance, harvest, storage, and transportation. Thus, the farmers will choose the optimal input mix to minimize the inputs costs. As the demander of switchgrass, the biorefinery is paid by the output produced, mainly ethanol. The biorefinery must take all the measurable inputs costs to produce ethanol into consideration. These costs mainly include costs paid to the farmers for switchgrass production, storage and transportation to the plant for processing. In this analysis, potential economies of size from the integrated switchgrass production by the biorefinery were also evaluated.

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PART 1: COST ANALYSIS OF ALTERNATIVE HARVEST, STORAGE AND TRANSPORTATION METHODS FOR DELIVERING SWITCHGRASS TO A BIOREFINERY FROM THE FARMERS' PERSPECTIVE

Abstract

Switchgrass for bioenergy production will require substantial storage. This study ascertained the costs of various baling and on-farm storage systems by simulating the final delivered costs to the biorefinery under two representative soil types in East Tennessee and West Tennessee. The impact of variations in switchgrass yields, diesel fuel prices, and nitrogen fertilizer prices on delivered costs at the biorefinery platn gate are considered. Results show that rectangular bales minimize cost if switchgrass is processed immediately after harvest. However, round bales minimize cost if switchgrass is stored without protection for 200 days before being transported to the biorefinery.

Introduction

Switchgrass is considered a potential leading energy crop for ethanol production (McLaughlin and Kszos 2005). For bioenergy production, the projected harvesting time for switchgrass is once in the fall after a killing freeze (Rinehart 2006). Nutrients then move into the root system, minimizing the harvest of nutrients and their replacement, and maximizing the lignocellulosic material for conversion to ethanol. Because switchgrass requires fewer inputs to grow and produces relatively large yields in semi-humid and humid environments, it is ideal for production on marginal lands in Tennessee (Tiller 2008). However, switchgrass is bulky, making it expensive to harvest, store and transport (Cundiff 1996). A once-a-year harvest, coupled with the large area required to store switchgrass, will likely require storage of a substantial amount of biomass away from the plant, either at a satellite area or on the farm (Larson 2008). In addition, weather affects not only switchgrass yield before harvest but also dry matter quantity and quality losses after harvest if switchgrass is stored without protection (English, Larson and Moony, 2008). Thus, biorefineries may require farmers to store harvested switchgrass under cover before being transported to the refining facility. Given the aforementioned issues, research is needed to evaluate the tradeoffs among different on-farm harvest and storage methods and arrangements.

Cundiff (1996) found that the harvest and transportation of switchgrass is an equipment-intensive enterprise, accounting for two-thirds of the final delivered cost, while the production accounts for one-third. Cundiff and Marsh (1996) compared harvest and on-farm storage costs for large round bales and rectangular bales. At the 3.64 dt/acre yield, harvest costs were $19.06/dt and $14.68/dt for round bales and rectangular bales. However, the storage costs were $3.83/dt and $16.97/dt for round bale and rectangular bale respectively. They found that the difference in costs becomes less significant, when the yield is above 3.64 dt/acre and storage losses for round bales stored outside increase above 5 percent.

Popp and Hogan (2007) evaluated two alternative harvesting and transportation methods (round bale and module harvested) that may be suitable for Arkansas conditions. The use of labor, storage protection (bale wrap and tarps), equipment intensity and final product (chopped or merely conditioned) were differentiated in these two systems. Sokhansanj, Eng and Fenton (2006), used the IBSAL model and found that the most important factors that affect the total delivered cost are the bulk density of biomass, moisture content, and the distance to be transported. Kumar and Sokhansanj (2007) employed the IBSAL model to estimate that the baling cost of switchgrass ranges from $44 to $47/dt delivered to a biorefinery. Although the prior research has evaluated costs of production ofswitchgrass as a feedstock for energy production, only a few of the studies took storage costs and storage losses into consideration. Not considering the costs of storage and dry matter loss during storage may underestimate the costs of production for switchgrass. This research evaluates the costs of alternative farm-level harvest, storage and transportation methods to deliver switchgrass to the biorefinery considering typical farm resources, farm constraints, and weather in Tennessee.

Conceptual Framework

Farmers are assumed to be price takers for inputs purchased and outputs sold and thus want to minimize production costs to maximize profits. As such, an individual farmer should attempt to reduce costs to achieve high profits from producing switchgrass. For this analysis, it is assumed that currently available hay equipment is used to establish, maintain, harvest, stage, and store switchgrass on the farm before it is transported to the processing plant. Since switchgrass is a perennial crop, it is only planted once in a lifespan of ten years or more. (Rinehart 2006) Thus, delivered costs to the plant including the opportunity cost on land; the establishment costs incurred in the first year of production; and the recurring annual costs for nutrients, pest control, harvest, storage, and transport can be modeled using:

Pre-harvest costs ($/acre):

$$\alpha = LAND + EST(d, f) + AMC(f), \tag{1}$$

Harvest costs ($/acre):

$$\beta_h = MOW_h(d) + RAKE_h(d) + LOADER_h(d, y) + BALER_h(d, y) + TRACTOR_h(d, y) + LABOR_h(y), \tag{2}$$

Post-harvest costs ($/dt): $$\beta_h{}^p = \frac{\alpha + \beta_h}{y(1-u_h)}, \tag{3}$$

Post-storage costs ($/dt): $$\gamma_{hst}{}^p = \frac{\beta_h{}^p + \gamma_{hst}}{(1-v_{hst})}, and \tag{4}$$

Delivered cost ($/dt): $$\theta_{hst}{}^p = \frac{\gamma_{hst}{}^p + \theta_{hst}}{(1-w_{hst})}. \tag{5}$$

where the subscript h is bale shape (round or rectangular); the subscript s is storage method; the subscript t is time in storage; *LAND* is the annual land rental rate; *EST* is switchgrass establishment expenses amortized over the life of a contract to produce switchgrass ($/acre); *AMC* is annual maintenance cost which includes costs of fertilization and pest control; *MOW, RAKE, BALE, STAGE*, and *STORE* are the labor, operating, and ownership costs of mowing, raking, baling, handling, and storing switchgrass ($/dt), respectively; μ is the dry matter loss during harvest; v is the dry matter loss during storage; w is dry matter loss during transportation; α is the pre-harvest cost; β is the harvest cost; γ is the storage cost; θ is the transport cost; β^p is the loss adjusted post harvest cost; γ^p is the loss adjusted post storage cost; and θ^p is the loss adjusted post transport cost to the biorefinery (delivered cost). The variables assumed to be random in the equations are diesel fuel price (d, $/gal), nitrogen fertilizer price (f, $/lb), switchgrass yield (y, ton/acre) and storage dry matter loss (v, %). After establishment, diesel fuel and fertilizer are the two most costly inputs that would be purchased in each year of production. If the land tested low in phosphate and/or potash, then additional nutrient costs may occur, but are not accounted for in calculating costs in this analysis (Gerloff 2008). Higher switchgrass yields incur more field time per acre to harvest and handle switchgrass, thus greater fuel, labor, and other operating and ownership costs and opportunity cost of land per hour. However, higher switchgrass yields lower the delivered cost when the cost is spread over tonnage. Storage dry matter loss is assumed to be affected both by the weather and days in storage.

Data and Methods

Switchgrass Harvest Storage Experiment Design

Dry matter loss data used in this research were from an ongoing switchgrass harvest and storage study at the Milan Research and Education Center (MREC) in Milan, Tennessee (English et al. 2008). The three treatments in the study were: bale harvest method, bale storage method and bale storage time. Large round bales (5 ft ×4 ft) and large rectangular bales (4 ft × 8 ft) were the two bale harvest treatments. Bale storage treatments in the experiment including covering or not covering the round and rectangular bales with a protective tarp on one of three storage surfaces: 1) well-drained ground, 2) a gravel surface, or 3) a wooden pallet. For the large round bales, the six storage treatments are: 1) uncovered on well-drained ground 2) uncovered on gravel, 3) uncovered on wooden pallets, 4) covered on well-drained ground, 5) covered on gravel, and 6) and covered on wooden pallets. For the rectangular bales, the four storage treatments are: 1) uncovered on gravel, 2) uncovered on wooden pallets, 3) covered on gravel, and 4) and covered on wooden pallets. The target bale storage times in the experiment that were used in this analysis were: 1) 0 days and 2) 200 days.

Switchgrass bales for each treatment were obtained from plots at the MREC and from farmer fields under contract with the University of Tennessee Switchgrass Project in Henry County, TN. The bales were placed into the storage experiment on January 24-25, 2008. Each bale harvest method, storage method and storage time treatment was replicated three times. The bales were randomly selected and placed into a treatment. The 108 large round bales and the 78 large rectangular bales were weighed and sampled to determine dry matter as they were placed into storage. At each storage time interval, three bales representing a particular treatment were weighed, mechanically separated in two halves, photographed and proportionally sampled based on a visual estimate of up to four weathered areas in each bale. The "wet sample weight" and "dry sample weight" were taken from weighing the wet samples at each storage interval and later weighing the same samples after drying them. The photograph of each bale sampled was imported into ArcGIS 9 and used to calculate the proportion of the bale in each weathered area. The formula used to calculate the dry weight per bale after each storage period (DWB_{hst}) is given by:

$$DWB_{hst} = WWB_{hst} \times \sum_{n=1}^{N} \left(WA_{hst,n} \times \frac{DSW_{hs,nt}}{WSW_{hst,n}} \right) \quad (6)$$

where WWB is the wet weight of the bale before sampling, WA is the proportion of the bale in weathered area n, DSW is the dry sample weight, and WSW is the wet sample weight. The dry weight per bale after harvest (DWB_{hs0}) can be viewed as the dry weight per bale after 0 days of storage. The storage dry matter loss (v) was obtained by dividing the difference between dry weight after harvest and dry weight after storage by the dry weight after harvest, which is shown in the following equation:

$$v_{hst} = \frac{DWB_{hs0} - DWB_{hst}}{DWB_{hs0}}. \quad (7)$$

The two storage times evaluated in this study using dry matter loss data from the experiment were 0-days in storage (i.e., assumes that the bales were taken immediately after harvest to the biorefinery for processing) and 200 days ins in storage before transportation to the biorefinery for processing.

Enterprise Budgeting

The costs of equipment assumed to be used in the establishment, maintenance, harvest, storage and transport of switchgrass is presented in Table 1 (All tables and figures are shown in Appendix). The equipment assumed for the round baling system included a 5 ft × 4 ft large round baler, a mower, a rake, and a loader and a tractor. The rectangular baling system differed from the round baling system by replacing the large round baler with a 4 ft × 8 ft rectangular baler. After harvested, all the switchgrass bales were transported by a tractor to the field edge and stored with or without tarps on bare ground, gravel or pallets. Semi-tractor trailers were assumed for switchgrass bale transportation from the farm to the biorefinery. Enterprise budgeting was employed to calculate the costs for each budget in accordance with the American Agricultural Economics Association Cost and Return Handbook (AAEA 2000) and American Society of Agricultural Engineers (ASAE) Standards (2000). Labor time was assumed to be 1.25 times the corresponding machine time (ASAE Standard 2000) and the wage for each operation was assumed to be $8.5/hour (Georlof 2008). The budget for the equipment used in establishment, annual maintenance, harvest, storage and transportation are listed through Table 1 to 6.

(1) Pre-harvest cost α

The pre-harvest costs were calculated for two contrasting agricultural soil types found in Tennessee. The Loring is typically found in West Tennessee and is characterized as being a moderately well-drained with a fragipan and slopes up to 20 percent (U.S. Department of Agriculture, Natural Resource Conservation Service 2003). Agricultural uses for the soils include cotton, small grains, soybean, hay and pasture (U.S. Department of Agriculture, Natural Resource Conservation Service 2003). Because the Loring soil is primarily used for crop production, a rental rate of $60/acre is charged as an opportunity cost and is based on the cropland rental rate reported by the Tennessee Agricultural Statistics Service in 2007 (Tennessee Agriculture 2008). By comparison, the Dandridge soil is typically found in East Tennessee and is characterized as being shallow, excessively drained, and with slopes ranging from 2 percent to 70 percent and the primary agricultural use of this soil is for pasture (U.S. Department of

Agriculture, Natural Resource Conservation Service 2003). The rental rate assumed for the Dandridge soil was $20/acre, the pasture land rental rate reported from 2007 by the Tennessee Agricultural Statistics Service (Tennessee Agriculture 2008). Establishment cost was amortized over 5 years based on the assumption of a potential contract period of 5 years (Table 2). Annual maintenance cost includes costs of nitrogen fertilizer and pesticide (Table 3).

(2) Harvest cost β_h

The cost of equipment per acre is the product of corresponding cost per hour obtained from enterprise budgeting and machine time of the equipment. The total harvest cost per acre is the sum of the per acre costs of mowing, raking, baling and staging. Machine time of the round balers is assumed to be linearly related to yield based on a throughput capacity of 5.5 dry tons per hour for switchgrass (Mooney et al. 2008). The machine times for mowing and raking were assumed not to vary with yield. Dry matter loss during harvest was assumed to be zero in this study.

(3) Storage cost γ_{hst}

The estimated costs for materials used for the storage of switchgrass bales including the sizes and prices for plastic tarps, gravel, and wooden pallets which were obtained from an informal survey from suppliers in Tennessee. Collins et al. (1997) found that the 3-2-1 pyramid design with three bales in the bottom, two in the middle and one on the top is practical and effective to shed water in the high precipitation environment found in Tennessee and the southeast United States. A 25 ft by 54 ft tarp was the assumed size used to cover both round and rectangular bales. Given the round bale size of 5 ft by 4 ft and the rectangular bale size of 4 ft by 8 ft, up to seventy-two round bales or sixty rectangular bales can be stored under one such tarp.

A gravel pad with a 5-inch depth was assumed as a base for placing bales. Thus, one ton of gravel was assumed to cover 32 sq ft on the ground and an average of three round bales or 2.5 rectangular bales can be placed in that area when a 3-2-1 pyramid is assumed. Three pallets were assumed for six round bales placed in one row of the 3-2-1 pyramid design. Four pallets were assumed needed for one row with five rectangular bales. Given the expected contract period of 5 years, the tarps, gravel and pallets were assumed to have 5 years of useful life. Thus, the costs of tarps, gravel and pallets were amortized over 5 years and assumed to have zero salvage value. Wooden pallets were assumed to be replaced at a rate of 20 percent per year. Tarps and gravel pads were assumed to have a replacement rate of 1 percent of initial cost for each year of use. The storage cost per ton (γ_{sh}) is sum of costs of the top cover, the bottom support, labor and pickup truck (Table 5).

(4) Transporation cost θ_{hst}

The cost per hour of the semi-tractor trailer was obtained using the same budget procedures as used for harvest. Assuming a draw area of 50 miles in a circle surrounding a biorefinery, the average distance traveled from the farm to the plant was assumed to be 37.5 miles (Hess 2007). The average travel speed of the semi-tractor trailer was assumed to be 50 miles/hour (Brechbill, Tyner, and Ileleji 2008). As a result, the time per round trip to the plant was assumed to be two hours. The capacity of the trailer was assumed to be 36 large round bales or 24 rectangular bales. Thus, the trailer carries 13 round bales or 6.5 rectangular bales per hour. The average bale density was assumed to be 0.4 tons/bale for the round bales and 1 tons/bale for the rectangular bales, so on average the trailer carries 13 tons of round bales per hour or 16 tons of rectangular bales per hour. Finally, the cost per ton of transportation (θ_{hst}^0) was obtained by dividing the cost per hour by tons per hour the trailer carries. Dry matter loss during transportation was assumed to be 2 percent for round bales and rectangular bales (Kumar and Sokhansanj 2007).

Simulation

Simulation was used to estimate probability distributions of switchgrass production costs for each bale type and storage treatments. The variables assumed to be random in the simulation were switchgrass yields, diesel fuel prices, and nitrogen fertilizer prices. One hundred years of switchgrass yields were simulated using the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al. 1996). The location of the weather station, soil types and nitrogen rates were the most important determinants for switchgrass yields. The latitude and longitude for the center of East Tennessee and West Tennessee were found to determine weather parameters for the simulation. The same nitrogen rates were assumed for the Loring and Dandridge soil types and were based on the University of Tennessee erosion recommendations (Gerloff 2008). Diesel fuel price and nitrogen fertilizer price were simulated using @Risk (Palisade Corporation 2007). Price data for estimating the nitrogen fertilizer and diesel fuel distribution parameters were obtained from the price report in Agricultural Statistics from 1977 to 2005 (U.S. Department of Agriculture-National Agricultural Statistics Service 2007). For each soil type, six cumulative density functions of delivered cost for round bales and four cumulative density functions of delivered cost for rectangular bales were obtained from the simulation using equations (1) through (5) based on variations of switchgrass yields, diesel fuel price and nitrogen fertilizer price under each storage period. Also, the same analysis was done for switchgrass that delivered to the plant immediately after being harvested which does not incur storage loss.

Results

Switchgrass yields

The simulated switchgrass yields on the East Tennessee Dandridge soil averaged 5.7dt/acre and varied between 2 and 11.2 dt/acre (Figure1). Switchgrass yields were generally higher on the more productive West Tennessee Loring soil, averaging 9.1 dt/acre, with a range of 1.7 to 15.6 dt/acre. For the Dandridge soil, there was a 39 percent probability that switchgrass yields would be 5 dt/acre or less compared with a 25 percent chance on the Loring soil. Results from the simulation indicate that switchgrass production was more risky on the Dandridge soil than on the Loring soil because of a higher probability of low yields.

Delivered cost immediately after harvest (without storage)

Simulated costs of production on a land-area basis were higher on the Loring soil than on the Dandridge soil. On the Dandridge soil, total production costs were $509/acre and $498/acre, respectively, for the round baling and rectangular baling system (not shown). By comparison, the average costs of production on the Loring soil were 36 percent and 30 percent more at $695/acre and $650/acre, respectively, for the round and rectangular baling systems (not shown). Higher yields which resulted in larger harvest costs coupled with a higher opportunity cost on land caused the higher production costs on a land-area basis on the Loring soil.

Despite the higher costs on a land-area basis for the Loring soil, the average costs per dry ton of biomass delivered immediately after harvest to the biorefinery were lower for the Loring soil than for the Dandridge soil. On the more productive West Tennessee Loring soil, the costs of biomass were $75/dt for the round bales and $72/dt for the rectangular bales (Table 7). By comparison, the average costs per ton on the less productive East Tennessee Dandridge soil were 19 percent ($14/dt) and 21 percent ($15/dt) higher for the round and rectangular bales, respectively (Table 7). Results indicate that rectangular bales had a lower average cost of production than round bales when storage costs and dry matter losses were not considered. A key assumption of this analysis was that both the round and rectangular balers were assumed to cover the same land area of 100 acres in each year of the simulation (Table 1). Because of the longer assumed useful life and the larger throughput capacity of the rectangular baler (Table 1), it seems more likely that there would be size economies with the rectangular baler than the round baler and thus the cost difference would likely be bigger on larger acreages.

The University of Tennessee Biofuels Initiative has a goal of having a delivered feed stock cost of $75/dt or less at the biorefinery plant gate (Garland 2009). For the more productive Loring soil, the probability of achieving delivered costs of $75/dt or less was 68 percent for round bales and 70 percent for rectangular bales when the biomass is immediately delivered after harvest to the biorefiney (Figure 2). By comparison, the probability of having delivered costs of $75/dt or less were considerably lower on the less productive East Tennessee Dandridge soil – 40 percent for round bales and 46 percent for rectangular bales (Figure 2).

The cumulative frequency distribution could also be used to evaluate the probability of positive net returns for a given switchgrass price that might be paid by the biorefinery. The frequency of net returns greater than zero for the rectangular bales is 70 percent on the Loring soil but only 46 percent on the Dandridge soil at a switchgrass price of $75/dt. The results indicate that production costs per ton were lower and the frequency of positive net returns for a given switchgrass price was higher on the more productive Loring soil. Thus, policy makers may want to target subside payments designed to reduce costs per dry ton to more marginal lands to maximize the potential environmental benefit of growing switchgrass which may include increased sequestration, reduced soil erosion, and enhanced water quality.

Storage loss (%) at 200 days in storage

The storage dry matter losses as a percentage of the initial bale dry matter weights for each protection treatment is shown in Table 8. After 200 days in storage, the covered round switchgrass bales staged on wood pallets generated the lowest average dry matter storage losses of 1.0 percent. The greatest storage losses for the round bales averaged 18.2 percent from storing on wood pallets without tarp to cover. The storage losses after 200 days in storage averaged 5.5 percent for round bales with a top cover and 15.9 percent for round bales without a top cover. Compared to the round bales, the rectangular bales had much larger dry matter storage losses. The lowest dry matter losses after 200 days in storage for the rectangular bales averaged 13.7 percent. The highest storage losses averaged 57.1 percent after 200 days in storage for the rectangular bales. The dry matter losses after 200 days in storage averaged 20.9 percent for rectangular bales with cover and 52.5 percent for rectangular bales without cover. Results indicate that storage dry matter losses of rectangular bales are greater than those of round bales under Tennessee weather conditions

Switchgrass delivered cost after 200 days in storage

Using the estimated storage dry matter losses from the Milan storage study, the simulation results indicate that round bales stored without protection had the lowest delivered cost among all of the ten harvest and storage treatments. On Loring soil, the delivered cost averaged $84.98/dt for unprotected round bales, which was $13.62/dt, or 13.8 percent cheaper than rectangular bales stored with tarps and pallets (Table 7). Using the target $75/dt delivered cost from The University of Tennessee Biofuels Initiative for the Loring soil, the probability that the delivered cost for unprotected round bales was less than $75/dt or less was 60 percent, compared with 68 percent when storage dry matter losses were not considered (Figure 3). For bales that were protected in some manner, the probabilities of production costs being $75/dt or less were much lower − 57 percent for round bales protected with tarps only, 56 percent for round bales protected with tarps and pallets, 36 percent for round bales protected with pallets only, 3 percent for round bales protected with tarps and gravel surface, and 2 percent for round bales protected with a gravel surface. The probabilities that the delivered cost was $75/dt or less were lower for the rectangular bales − 56 percent for rectangular bales protected with tarps and pallets, 2 percent for rectangular bales protected with tarps and gravel, and 0 percent for other forms of protection.

On the less productive Dandridge soil, the delivered cost averaged $100.54/dt for round unprotected bales, which is $20.44/dt or 16.9 percent lower than rectangular bales stored with tarps and pallets (Table 7). The probabilities that the delivered cost was $75/dt or less when storage costs were considered were much lower on the less productive Dandridge soil − 17 percent for round unprotected bales, 3 percent for round bales protected with tarps only, 2 percent for round bales protected with tarps and pallets, 1 percent for round bales protected with pallets only, and 0 percent for other forms of protection. The probability that the delivered cost was $75/dt or less is 1 percent for rectangular bales protected with tarps and pallets, and almost zero for other forms of rectangular bales (Figure 3).

As can be seen, after 200 days in storage, the delivered costs of switchgrass on Loring soil increased at least $9.48/dt, or 12.6 percent and the delivered costs of switchgrass on Dandridge soil increased at least $11.47/dt, or 12.9 percent (Table 7). This cost increase was accompanied by a switch in the harvest method. The optimal switchgrass harvest method switched from rectangular baling to round baling after 200 days in storage mainly due to the dry matter losses incurred with storage. Switchgrass stored without protection is the optimal storage method in terms of delivered cost after 200 days in storage.

Breakeven analysis

As described previously, switchgrass harvested using the round baling system and stored without protection yielded the lowest delivered cost after 200 days in storage. The dry matter losses from the storage experiment were estimated for single bales that were not part of a large stack. Therefore, the dry matter losses used to calculate production costs under alternative storage methods may overestimate the dry matter losses during storage and thus production costs. Using the budget values in Table 7, the storage dry matter loss which provides the equivalent delivered cost as round bales stored without protection was recalculated for each harvest and storage treatment. As shown in Table 9, the storage dry matter losses for the round bales produced on Loring soil and stored with protection would need to be negative to have the same delivered costs as the round bales stored without protection. This indicates that the costs of materials used to protect the bales would need to be lower than what was estimated in this study. The storage dry matter loss of the rectangular bales produced on Loring soil and stored with tarp and pallet would need to be lowered from 13.7 percent to 3.1 percent to have the same delivered cost as the round bales stored without protection. It is impossible for the round bales stored with gravel or tarp to breakeven with the round bales that stored without protection at any non-negative dry matter loss level due to the high cost of gravel. Sensitivity on the cost of storage for each treatment shows that at the estimated dry matter loss level, storage cost would need to be lowered substantially to breakeven with the storage without protection treatment (Table 9). For example, on Loring soil, the cost of tarp would need to be decreased from $4.81/dt to $2.09/dt to breakeven with the storage without protection option.

Sensitivity of delivered cost to switchgrass yield

In order to evaluate the sensitivity of the delivered cost to switchgrass yield, the delivered cost for each harvest and storage treatment were calculated under 3 dt/acre, 6 dt/acre, 9 dt/acre and 12 dt/acre switchgrass yields. As can be seen, the delivered cost was more responsive to switchgrass yield for the rectangular bales than for the round bales for each storage treatment when switchgrass yield is below 12 dt/acre (Figure 4). When switchgrass yield was increased from 3 dt/acre to 6 dt/acre, the delivered cost decreased by $73.08 dt/acre for rectangular bales stored with tarp and pallet and by $50.05 dt/acre for round bales without protection. When switchgrass yield was increased from 6 dt/acre to 9 dt/acre, the delivered cost decrease by $27.78 dt/acre for rectangular bales stored with tarp and pallet and by $16.78 dt/acre for round bales stored without protection. However, when switchgrass yield was increased from 9 dt/acre to12dt/acre, the delivered cost decreased by $11.94 dt/acre for rectangular bales stored with tarp and pallet and by $13.24 dt/acre for round bales stored without protection.

Summary and Conclusions

The analysis shows that the costs to harvest and transport the rectangular bales were lower than the corresponding costs to deliver the round bales to the biorefinery, when storage costs and storage losses were not considered. However, the biorefinery may ask farmers to deliver their switchgrass to the plant in different periods to maintain a steady supply of switchgrass. Thus, farmers may need to store switchgrass for after harvest. For switchgrass delivered after 200 days in storage, the round bales would be less expensive per dry ton. The results from this study show that dry matter losses, especially with rectangular bales, have a substantial influence on the cost per dry ton of switchgrass delivered to the plant. When switchgrass is delivered after 200 days in storage, round bales without protection were the least cost.

A key assumption of this analysis was that both round and rectangular balers were assumed to cover the same 100 acres of land area in each year of the simulation. Because of the longer assumed useful life and the larger throughput capacity of the rectangular baler, it seems likely that there would be size economies with the rectangular baler than the round baler and thus the cost difference would likely be bigger on larger acreages. Results indicate as the time in storage increases, the least cost harvest method switchs from rectangular baling to round baling. It is predictable that rectangular bales would be preferred when the dry matter loss of storing the rectangular bales is very small, so the biorefinery may use rectangular baling system to harvest switchgrass that would be stored for a short period and use round baling system to harvest switchgrass that would be stored for a relatively long period. However, if this requires the conversion facility to have two separate handling systems, then these savings would need to be weighed against the costs of that additional system.

Further research and data on the dry matter losses as a function of time or weather variables for different storage treatments will be needed to estimate the appropriate compensation for farmers who may be required to store the harvested switchgrass for different periods. This study differs from other research on switchgrass delivered cost by incorporating the storage loss of each harvest and storage treatment and uses real data from the storage study at Milan Research and Education Center and provides farmers with better estimates on the costs of delivering switchgrass to the biorefinery. Similar analysis should be done from the biorefinery's perspective to test whether economies of scale can be achieved when the production and delivery of switchgrass are integrated by the biorefinery.

There are several limitations in this analysis. First, the round and rectangular balers are assumed to be used on 100 acres of land per year in a representative farm. However, farmers may not want to dedicate all their lands to switchgrass production. In reality, the land available to switchgrass production may be much less than 100 acres, especially in East Tennessee. The independent farm level switchgrass production might not be efficient due to the high fixed costs of machinery. Analysis on large scale switchgrass production such as from contracting farm cooperative which provides more land, shares production equipment and thus spreads the fixed costs of production on a large scale will provide valuable information.

Second, only two storage time periods were studied in this analysis. However, it is likely that the biorefinery requires switchgrass delivery at different time periods. As a result, the average storage losses are higher for switchgrass that delivered earlier than 200 days in storage and lower for switchgrass that delivered later than 200 days in storage. When the storage losses over time are obtained from the experiment, the tradeoff between harvest and storage will be better understood.

There are other limitations that should be taken into consideration in future study. The quality of the switchgrass dry matter delivered to the plant was not considered in this analysis.

The experiment data used in this research are based on the weather and observation in 2008, so the annual variations in weather were not explicitly considered in this study.

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Appendix

Table 1.1 Machinery Equipment Costs for Switchgrass in East Tennessee

Cost of Item	Drill	Sprayer	Round Baler	Rectangular Baler	Mower	Rake	Front End Loader	Tractor 215HP Round	Tractor 215HP Rectangular	Pickup Truck	Semi-Tractor
Basic Parameters											
Purchase Price[a] ($)	17,000	8,400	23,000	87,700	6,500	3,000	7,500	143,000		25,000	120,000
Hours of Useful Life[a] (hours)	1,500	1,500	1,500	3,000	2,000	2,500	1,000	12,000		12,000	22,000
Hours of Use Per Year (hours/year)	100	100	90.91	41.67	23.57	15.28	55.00	184.76	135.52	300	1,000
Fuel Price[d] ($/gallon)	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83		1.83	1.83
Fuel Use[b] (gallon/hour)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.42		2.00	22.12
Lubrication Factor[c] (%)	15.00%	15.00%	15.00%	15.00%	15.00%	15.00%	15.00%	15.00%		15.00%	15.00%
Interest Rate[c] (%)	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%		3.00%	3.00%
Housing % of PP[c]	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%		0.75%	0.75%
Tax Rate % of PP[c]	1%	1%	1%	1%	1%	1%	1%	1%		1%	1%
Insurance % of PP[c]	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%		0.25%	0.25%
Useful Years	15.00	15.00	7.14	30.00	15.04	20.83	10.00	18.02		18.00	22.00
Salvage Value ($)	1,700.0	840.00	9,137.0	9,083.29	1,874.5	711.45	2,707.0	30,061.4		2,500.0	18,171.1
Ownership Costs ($/hour)	18.70	9.24	21.97	113.77	14.51	9.86	10.92	42.69	55.18	5.70	9.33
Capital Recovery ($/hour)	13.60	6.72	16.91	71.68	8.99	5.94	8.20	27.21	34.07	0.14	6.93
TIH ($/hour)	5.10	2.52	5.06	42.10	5.52	3.93	2.73	15.48	21.10	7.73	2.4
Operating Costs ($/hour)	8.50	3.92	16.09	24.85	5.71	0.87	4.06	33.95		17.83	68.29
Diesel Fuel ($/hour)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.23		6.30	40.48
Lubrication Costs ($/hour)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.58		0.95	6.07
Repair ($/hour)	8.50	3.92	16.09	24.85	5.71	0.87	4.06	14.13		2.08	21.74
Total Machinery Cost ($/hour)	27.20	13.16	38.07	138.62	20.22	10.73	14.98	76.64	89.13	25.20	77.63

[a] Gerloff, 2008 except for the price of rectangular baler.
[b] Calculated from Agricultural and Applied Economics Association and American Society of Agriculture Engineers Standards (AAEA and ASAE), 2000.
[c] AAEA and ASAE, 2000.
[d] From simulation.

Table 1.2 Establishment Budget for Switchgrass in East Tennessee

Cost of Item	Unit	Quantity	Unit Price	Establishment Costs
Variable Expenses[a]				
Seed	Lbs/Acre PLS	*75*	$20.00	$150.00
Herbicide				
Roundup Original Mix	Pt/Acre	3.2	$2.24	$7.17
Cimarron	Oz/Acre	0.1	$19.00	1.9
Grass herbicide	App/Acre	3	$7.00	$21.00
Operating Capital	%	*Varies*	8	$7.83
Machinery Expenses[b]				
Diesel Fuel	Gal/Ac	4.17	$1.83	$10.11
Repair and Maintenance	Acre	1	$9.79	$9.79
Depreciation	Acre	1	$9.01	$9.01
Labor Expenses[a]				
Operator Labor	Hrs/Acre	0.62	$8.50	$10.39
Total Establishment Cost	$/Acre			$229.87
Amortized Establishment Cost	$/Acre/Year			$51.33

[a] Gerloff, 2008.
[b] Calculated from AAEA and ASAE standards.

Table 1.3 Annual Maintenance Budget for Switchgrass in East Tennessee

Cost of Item	Unit	Unit Price	Quantity	Production Costs
Variable Expenses				
Fertilizer				
Nitrogen	Lbs/Acre	$0.42	*60*	$25.20
Herbicide				
Cimarron	Oz/Acre	$19.00	0.1	$1.90
Grass herbicide	Aplic/Acre	$7.00	1	$7.00
Operating Capital	%	8		$1.46
Machinery Expenses				
Diesel Fuel	Gal/Acre	$1.83	*Varies*	$1.39
Repair and Maintenance	Acre	*Varies*	1	$1.17
Depreciation	Acre	*Varies*	1	$0.31
Labor Expenses				
Operator Labor	Hr/Acre	$8.50	3.93	$1.06
Total Annual Maintenance Cost	$/Ac			$40.66

[a] Gerloff, 2008.
[b] Calculated from AAEA and ASAE standards.

Table 1.4 Annual Harvest Budget for Switchgrass Produced on Loring and Dandridge Soil types

Cost of Item		Round Baler	Rectangular Baler	Mower	Rake	Loader	Tractor with		Total	
							Round	Rectangular	Round	Rectangular
Operating Cost ($/hour)		16.09	24.85	5.71	0.87	4.06	31.36	31.36		
Diesel & Lubrication (gallon/hour)		0.00	0.00	0.00	0.00	0.00	9.42	9.42		
R&M ($/hour)		16.09	24.85	5.71	0.87	4.06	14.13	14.13		
Ownership Cost ($/hour)	Loring	15.80	72.89			6.61	39.61	64.20		
	Dandridge	20.33	102.10	14.51	9.86	8.11	52.71	83.27		
Capital Recovery ($/hour)	Loring	13.00	49.63			5.62	25.55	39.17		
	Dandridge	15.91	65.32	8.99	5.94	6.54	32.70	50.22		
TIH ($/hour)	Loring	2.80	23.26			0.99	14.06	25.03		
	Dandridge	4.42	36.78	5.52	3.93	1.57	20.01	33.05		
Machinery Cost ($/hour)	Loring	31.89	97.73			10.67	70.98	95.56		
	Dandridge	36.42	126.94	20.22	10.73	12.17	84.08	114.63		
Machine Time (hours/acre)	Loring	1.65	0.75			1.51	3.54	2.65		
	Dandridge	1.04	0.48	0.24	0.15	0.95	2.38	1.82		
Machinery Cost ($/acre)	Loring	52.47	73.71			16.10	205.7	169.52		
	Dandridge	37.90	60.54	4.77	1.64	12.17	158.58	135.68		
Wage[a] ($/hour)		0.00	0.00	0.00	0.00	0.00	8.50	8.50		
Labor Time (hours/acre)	Loring						4.43	3.31		
	Dandridge						2.98	2.27		
Labor Cost ($/acre)	Loring						37.64	28.17		
	Dandridge						25.32	19.33		
Harvest Cost ($/acre)	Loring	52.47	73.71			16.10	243.34	197.69	318.32	293.91
	Dandridge	37.90	60.54	4.77	1.64	12.17	183.90	155.01	239.82	233.56
Harvest Cost ($/dt)	Loring	5.80	8.14	0.53	0.18	1.78	26.89	21.84	35.17	32.48
	Dandridge	6.62	10.58	0.83	0.29	2.03	32.13	27.08	41.90	40.81

[a] Gerloff, 2008.

Table 1.5 Annual Costs[a] for Storing Switchgrass for 200 days in East Tennessee

Bale Type	Storage Method	Cost/ Stack	Cost/ Bale	Cost/ Acre	Cost/Ton at Capacity		Cost/Ton at average yield	
					15 dt/acre on Loring soil	11 dt/acre on Dandridge soil	9 dt/acre on Loring soil	5.72 dt/acre on Dandridge soil
Rectangular Bale w/ Tarp on Pallets								
	25' by 54' tarp	$72.77	$1.21	$22.45	$2.04	$2.04	$3.40	$3.92
	48 pallets	$105.57	$1.76	$32.56	$2.96	$2.96	$4.93	$5.69
	Labor to place cover	$5.67	$0.09	$1.75	$0.16	$0.16	$0.26	$0.31
	Labor to place pallets	$5.67	$0.09	$1.75	$0.16	$0.16	$0.26	$0.31
	Pickup truck cost	$9.82	$0.16	$3.03	$0.28	$0.28	$0.46	$0.53
	Total	$199.49	$3.32	$61.53	$5.59	$5.59	$9.32	$10.76
Rectangular Bale w/o Tarp on Pallets								
	25' by 54' tarp	$0.00	$0.00	$0.00	$0.00			
	48 pallets	$105.57	$1.76	$32.56	$2.96	$2.96	$4.93	$5.69
	Labor to place cover	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	Labor to place pallets	$5.67	$0.09	$1.75	$0.16	$0.16	$0.26	$0.31
	Pickup truck cost	$9.82	$0.16	$3.03	$0.28	$0.28	$0.46	$0.53
	Total	$121.05	$2.02	$37.34	$3.39	$3.39	$5.66	$6.53
Rectangular Bale w/ Tarp on Gravel Pad								
	25' by 54' tarp	$72.77	$1.21	$22.45	$2.04	$2.04	$3.40	$3.92
	Gravel pad for stack	$294.17	$4.90	$90.74	$8.25	$8.25	$13.75	$15.86
	Labor to place cover	$5.67	$0.09	$1.75	$0.16	$0.16	$0.26	$0.31
	Pickup truck cost	$9.82	$0.16	$3.03	$0.28	$0.28	$0.46	$0.53
	Total	$382.42	$6.37	$117.96	$10.72	$10.72	$17.87	$20.62
Rectangular Bale w/o Tarp on Gravel Pad								
	25' by 54' tarp	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	Gravel pad for stack	$294.17	$4.90	$90.74	$8.25	$8.25	$13.75	$15.86
	Labor to place cover	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	Pickup truck cost	$9.82	$0.16	$3.03	$0.28	$0.28	$0.46	$0.53

Continued Table 5

Total	$303.99	$5.07	$93.76	$8.52	$8.52	$14.21	$16.39
Round Bale w/o Tarp on Pallets							
36 Pallets	$79.17	$1.10	$39.53	$3.59	$3.59	$5.99	$6.91
Labor to place pallets	$5.67	$0.08	$2.83	$0.26	$0.26	$0.43	$0.49
Pickup truck cost	$9.82	$0.14	$4.90	$0.45	$0.45	$0.74	$0.86
Total	$94.66	$1.31	$47.26	$4.30	$4.30	$7.16	$8.26
Round Bale w/o Tarp on Gravel Pad							
Gravel pad for stack	$306.59	$4.26	$153.07	$13.92	$13.92	$23.19	$26.76
Total	$306.59	$4.26	$153.07	$13.92	$13.92	$23.19	$26.76
Round Bale w/ Tarp on Ground							
25' by 54' tarp	$93.72	$1.30	$46.79	$4.25	$4.25	$7.09	$8.18
Labor to place cover	$5.67	$0.08	$2.83	$0.26	$0.26	$0.43	$0.49
Pickup truck cost	$6.48	$0.09	$3.24	$0.29	$0.29	$0.49	$0.57
Total	$105.87	$1.47	$52.86	$4.81	$4.81	$8.01	$9.24
Round Bale w/ Tarp on Pallets							
25' by 54' tarp	$68.79	$0.96	$34.35	$3.12	$3.12	$5.20	$6.00
36 Pallets	$79.17	$1.10	$39.53	$3.59	$3.59	$5.99	$6.91
Labor to place cover	$5.67	$0.08	$2.83	$0.26	$0.26	$0.43	$0.49
Labor to place pallets	$5.67	$0.08	$2.83	$0.26	$0.26	$0.43	$0.49
Pickup truck cost	$9.82	$0.14	$4.90	$0.45	$0.45	$0.74	$0.86
Total	$169.12	$2.35	$84.44	$7.68	$7.68	$12.79	$14.76
Round Bale w/ Tarp on Gravel Pad							
One 25' by 54' tarp	$68.79	$0.96	$34.35	$3.12	$3.12	$5.20	$6
Gravel pad for stack	$306.59	$4.26	$153.07	$13.92	$13.92	$23.19	$26.76
Labor to place cover	$5.67	$0.08	$2.83	$0.26	$0.26	$0.43	$0.49
Pickup truck cost	$9.82	$0.14	$4.90	$0.45	$0.45	$0.74	$0.86
Total	$390.87	$5.43	$195.15	$17.74	$17.74	$29.57	$34.12

[a] Calculated based on AAEA and ASAE Standards.

Table 1.6 Annual Transportation Cost for Switchgrass in East Tennessee

Cost of Item	Round	Rectangular
Semi-Tractor Trailer ($/hour)	77.63	77.63
Speed (miles/hour)	50	50
Distance (miles)	37.2	37.2
Wage ($/hour)	8.50	8.50
Loading Time (hours/load)	0.75	0.75
Bales/Load (#)	36	24
Bale Weight (tons/bale)	0.37	0.67
Weight Per Load (tons)	13.18	16.01
Weight Transported (tons/hour)	8.85	10.76
Semi-Tractor Trailer Cost ($/dt)	8.77	7.22
Driver ($/dt)	1.44	1.19
Loader/Unloader Cost ($/dt)	0.48	0.40
Transportation Cost ($/dt)	10.69	8.80

[a] Calculated based on AAEA and ASAE Standards.

Table 1.7 Switchgrass delivered cost per ton for
i) switchgrass is delivered immediately after harvest, and ii) after 200 days in storage[a]

Item	Statistics	Large Round Bale		Large Rectangular Bale	
		Loring	Dandridge	Loring	Dandridge
		-----------------------------$/dt	-----------------------------	-----------------------------	-----------------------------
Delivered immediately after harvest					
None	Mean[b]	75.50	89.07	72.18	87.07
	Median[b]	59.88	80.10	55.04	76.28
	Budget Value[c]	*64.09*	*81.01*	*59.76*	*77.95*
Delivered after 200 days in storage					
Tarp + Pallet	Mean[b]	94.39	114.24	98.60	120.98
	Median[b]	72.04	100.15	73.70	104.27
	Budget Value[c]	*77.74*	*102.45*	*79.51*	*107.38*
Tarp + Gravel	Mean[b]	127.09	157.29	132.13	164.61
	Median[b]	93.45	135.60	95.80	140.48
	Budget Value[c]	*101.82*	*139.37*	*104.55*	*144.96*
Tarp only	Mean[b]	92.51	111.20	------	------
	Median[b]	71.17	98.01	------	------
	Budget Value[c]	*76.83*	*100.10*	------	------
Pallet only	Mean[b]	102.22	122.97	146.21	180.01
	Median[b]	78.61	108.35	108.20	155.15
	Budget Value[c]	*84.81*	*110.65*	*117.34*	*159.43*
Gravel only	Mean[b]	127.59	157.09	203.37	253.82
	Median[b]	94.75	136.07	147.22	216.01
	Budget Value[c]	*102.89*	*139.58*	*160.47*	*223.24*
None	Mean[b]	84.98	100.54	------	------
	Median[b]	67.18	90.34	------	------
	Budget Value[c]	*71.90*	*91.29*	------	------

[a] All costs are in reported 2007 dollars.
[b] Mean and Median are the mean value and median value from the simulation
[c] Budget value is based on switchgrass yield of 9.0 dt/acre on Loring soil and 5.7 dt/acre on Dandridge soil, diesel fuel price of $1.83/gallon and nitrogen fertilizer price of $0.40/lb, the average simulated values in the analysis.

Table 1.8 Dry matter losses[a] (%) after 200 days in storage

Storage Method	Large Round Bale	Large Rectangular Bale
Tarp + Pallet	1.0	13.7
Tarp + Gravel	8.5	28.0
Tarp	7.0	------
Pallet	18.2	48.0
Gravel	16.6	57.1
None	12.8	------

[a] Calculated from unpublished work from Burton English, James Larson and Don Tyler at Milan Research and Education Center.

Table 1.9 Breakeven analysis[a]

Bale type / Soil type	Tarp+Pallet	Tarp+Gravel	Tarp	Pallet	Gravel	None
	~~percent of dry matter loss during storage~~~~~~~~~~					
Round						
Original	*1.0*	*8.5*	*7.0*	*18.2*	*16.6*	*12.8*
Loring	−8.5	−36.4	−0.5	0.9	−25.8	12.8
Dandridge	−12.7	−46.2	−3.2	−1.5	−33.5	12.8
Rectangular						
Original	*13.7*	*28.0*	-----	*48.0*	*57.1*	-----
Loring	3.1	−9.6	-----	10.2	−3.6	-----
Dandridge	−3.4	−19.2	-----	4.8	−12.0	-----
	~~cost of storage ($/dt)~~~~~~~~~~~~~~~~~~					
Round						
Original	*7.68*	*17.74*	*4.81*	*4.30*	*13.92*	*0.00*
Loring	4.26	1.55	2.09	−1.95	−1.37	0.00
Dandridge	3.54	1.29	1.74	−1.62	−1.14	0.00
Rectangular						
Original	*5.59*	*10.72*	-----	*3.39*	*8.52*	-----
Loring	1.71	−3.18	-----	−10.58	−13.94	-----
Dandridge	0.40	−3.73	-----	−9.85	−12.64	-----

[a] What the dry matter losses or costs should be for the other 9 harvest and storage treatment to have the same delivered cost as the round bales that stored without protection on Loring and Dandridge soils respectively.

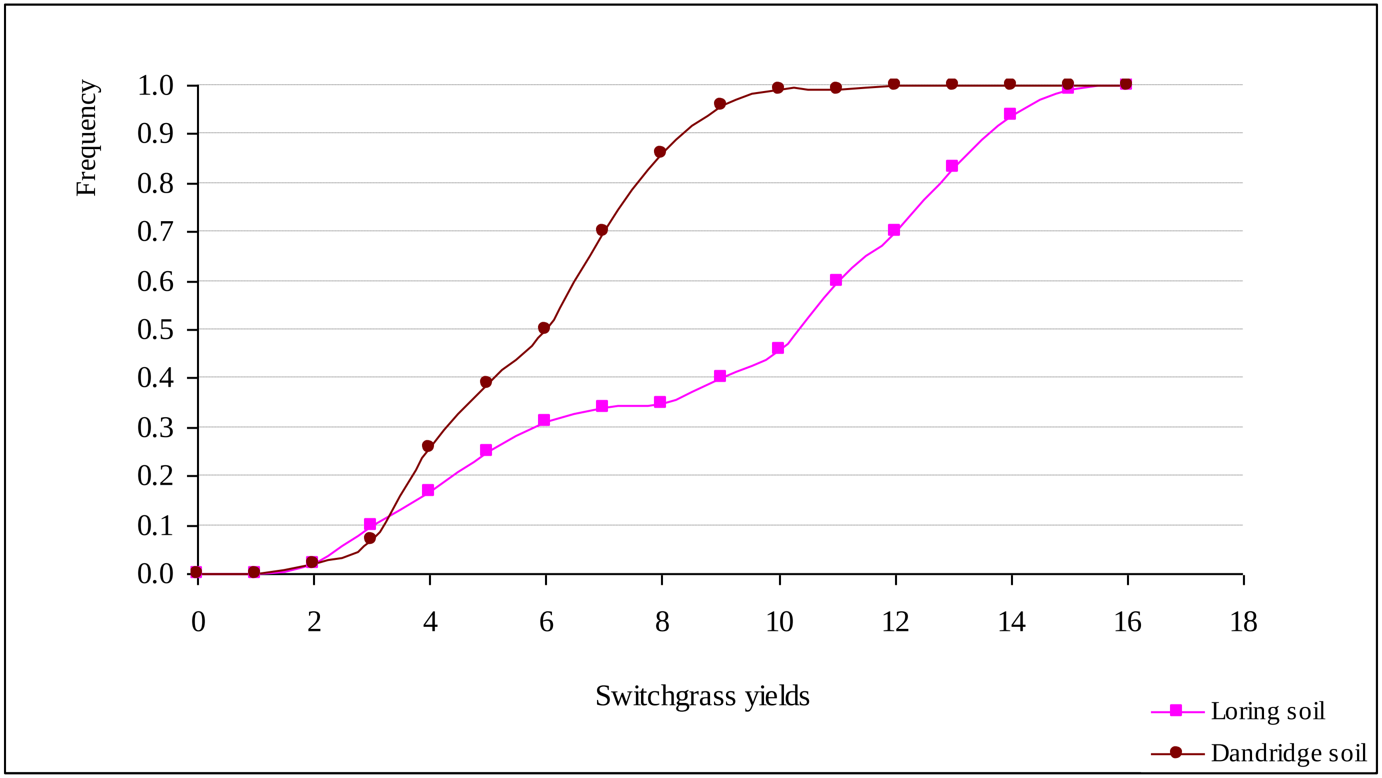

Figure 1.1 Cumulative frequency of switchgrass yields on Loring and Dandridge soils

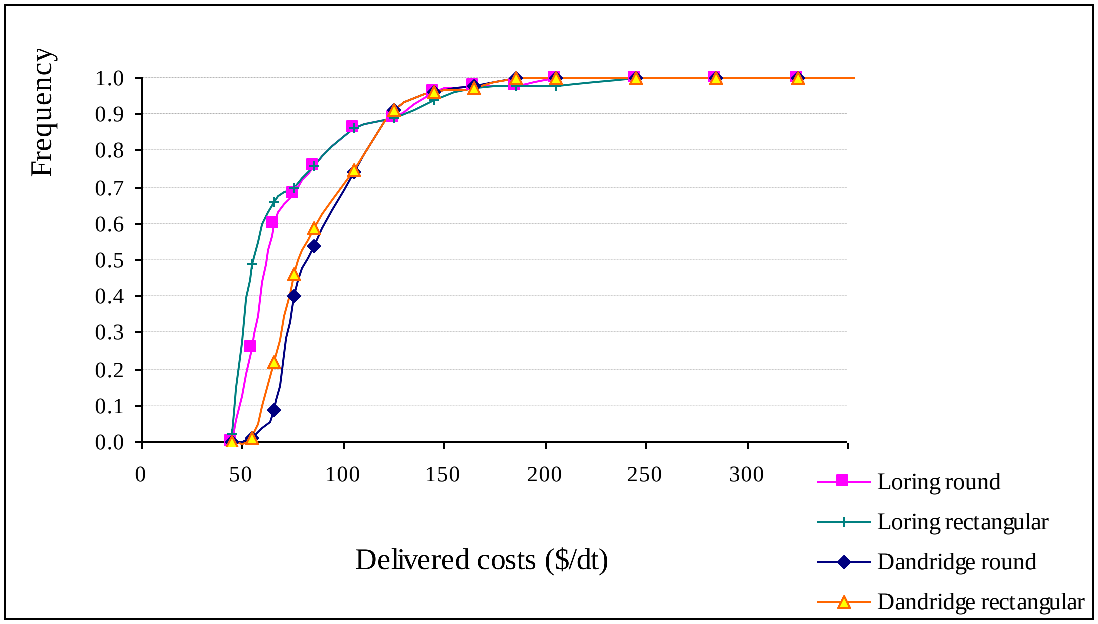

Figure 1.2 Cumulative frequency of switchgrass delivered costs immediately after harvest

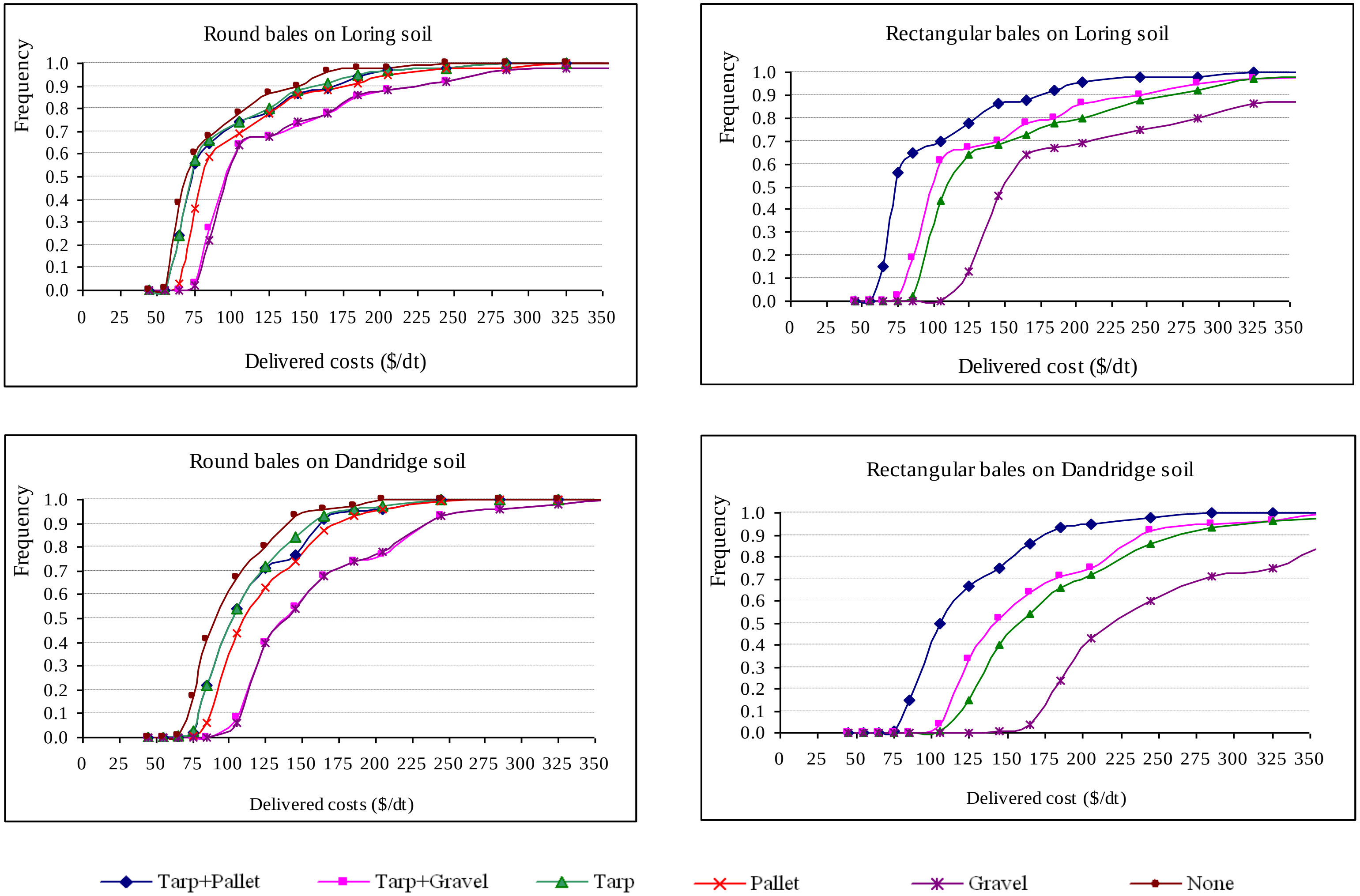

Figure 1.3 Cumulative frequency of switchgrass delivered costs after 200 days in storage

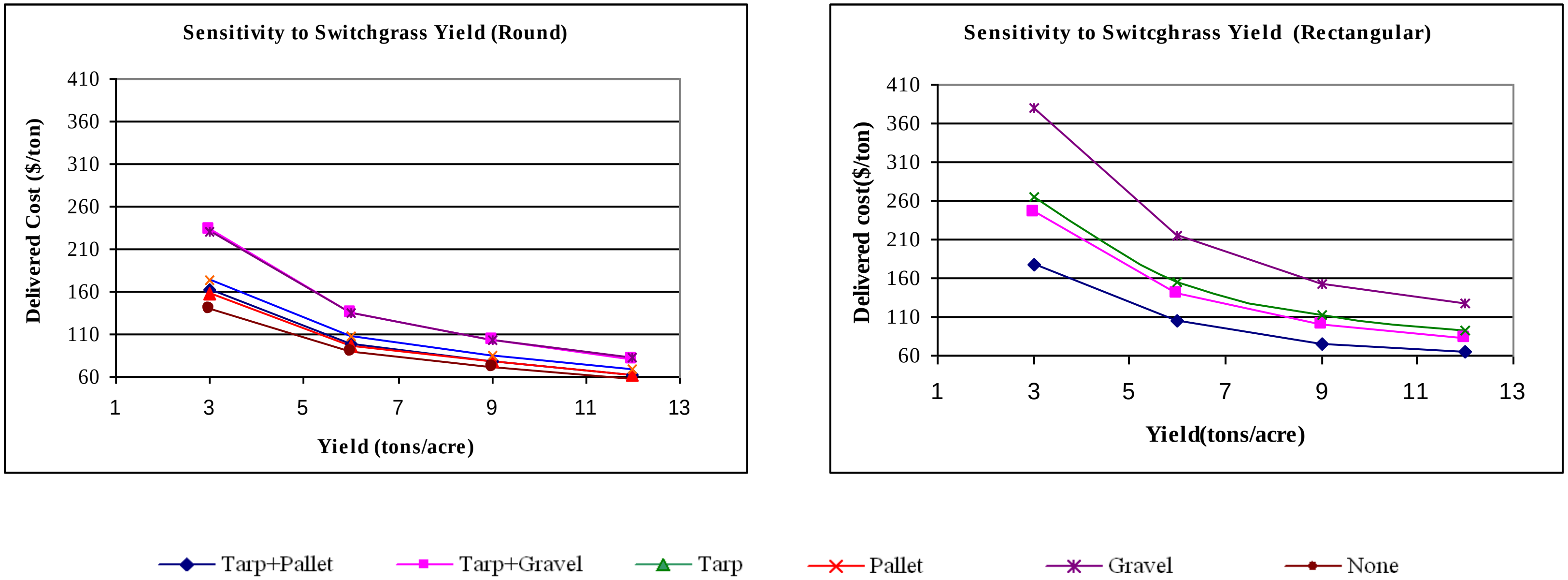

Figure 1.4 Sensitivity of delivered costs after 200 days in storage to switchgrass yield

PART 2: LOGISTIC OPTIMIZATION OF DELIVERING SWITCHGRASS TO A BIOREFINERY FROM THE PROCESSORS' PERSPECTIVE

Abstract

This study determines from the processors' perspective the least cost delivery schedule for switchgrass to a biorefinery considering bale types and storage methods. A mixed integer programming model was used to optimize the year round switchgrass delivery schedule within 50 miles of the biorefinery in East Tennessee from the processors' perspective, while minimizing the annual costs of delivering switchgrass. The delivery is constrained by land availability, switchgrass yields, field days for harvest, and storage dry matter losses. Scenario analyses for different plant sizes, harvesting systems, existence of storage losses and equipment efficiency were done in this study. Results from the base model show that the delivered cost, which accounts for $0.73/gallon of ethanol produced, is almost twice the U.S. Department of Energy's National Renewable Energy Laboratory's goal for feedstock production in 2012.

Introduction

Switchgrass, a warm season perennial grass native to the United States, is widely recognized as a potential leading crop for energy production (McLaughlin et al. 2002). It is a hardy, drought resistant plant that can grow in a variety of soils. Because switchgrass can grow on marginal soils that might not be suitable for other crops, it has the potential to open up new markets for farmers in Tennessee (Tiller 2008). Notwithstanding the potential benefits of growing switchgrass on marginal soils, there are a number of potential challenges to be overcome. The projected harvest time for switchgrass is one in the fall after a killing freeze (Rinehart 2006). After a freeze, nutrients move into the root system, minimizing the harvest of nutrients and their replacement, and maximizing the lignocellulosic material for conversion to ethanol. Thus, the projected time for harvesting switchgrass in Tennessee would occur in late fall or early winter when sunlight hours are limited and precipitation is high (U.S. Department of Commerce 2008). In addition, switchgrass is a bulky material relative to the energy contained, so it is relatively expensive to harvest, store, and transport to the biorefinery. On one hand, abundant rainfall and sunshine tend to increase switchgrass yields in Tennessee. On the other hand, higher precipitation in the fall and winter may limit field days and increase harvest time and biomass losses relative to other potential harvest periods (Hwang and Epplin 2007).

The once-a-year harvest for switchgrass, coupled with the relative bulkiness of biomass and the high precipitation in Tennessee may have several implications for a biorefinery that would require a steady supply of feedstock throughout the year. Because of the large area needed for the material storage, a substantial amount of biomass may need to be stored away from the plant and on the farm (Larson 2008). Precipitation and weathering may have a substantial influence on dry matter losses and quality of material delivered to the plant (Wiselogel et al. 1996; Sanderson et al. 1997). In addition, the weight of biomass materials being transported to the biorefinery may be impacted by the level of exposure to precipitation while switchgrass being store on the farm (Larson 2008). Uncovered on farm storage may increase transportation costs to the biorefinery as well, especially in areas such as Tennessee that have substantial precipitation. Given the potential problems with dry matter and quality losses, the biorefinery may require that stored bales be protected from precipitation and weathering. Research is needed under Tennessee growing conditions to evaluate the tradeoffs of different on-farm harvest and storage methods. It should provide farmers, potential biorefineries, and other potential stockholders with information to make least cost choices with regard to biomass crop production. In addition, information is needed on how the emerging industry of interrelated feedstock producers, biorefineries, and other service providers such as transportation and storage will be best conducted and how each will bear and share costs. Analysis by Bhat et al. (1992), Cundiff (1996), Cundiff and Marsh (1996), Cundiff et al. (1997), Epplin (1996), Thorsell et al. (2008), Maperoba et al (2007), Kumar and Sokhansanj (2007) and Popp and Hogan (2007) have evaluated some of the aspects of the logistics and costs of harvest, storage and transportation of biomass feedstocks, but not under Tennessee growing conditions.

Cundiff, Dias, and Sherali (1997) estimated the schedules for shipping biomass from farmers' storage facilities to the central plant under weather uncertainty. Tembo, Epplin and Huhnke (2003) determined the regions which are the most economically suitable for Oklahoma, timing of harvest and storage, inventory management, biorefinery size and location as well as the breakeven price of ethanol by their mixed integer model. Kumar, Sokhansanj, and Flynn (2006) developed a multi-criteria assessment model to rank alternative systems for biomass collection and transportation. Thorsell et al. (2004) specified the least cost set of machiney and estimated the costs of supplying a biorefinery for different annual capacities. Wilson et al. (2008) developed a spatial optimization model to project cropping patterns and grain shipments as ethanol expands. Petrolia (2008) found that farmers do not have incentives to violate soil erosion constraints as the demand for corn stover as a ethanol feedstock increases.

With a projected capacity of 2 to 4 million gallons of ethanol per year, a small-scale biorefinery is planned to be operational in 2010 in Vonore, Tennessee (Tiller 2008). When the small-scale biorefinery shows economical viability, it will be expanded to a commericial size which is at least ten times it. The candidate counties for drawing feedstock were assumed to be Blount, Bradley, Knox, Loudon, McMinn, Meigs, Monroe, Polk, Rhea and Roane which locate within 50 miles of the biorefinery in Monroe County. The plant will contract with farmers in those counties for the production of switchgrass (Garland 2009). Obviously, the amount of land that should be contracted to maintain a steady supply flow changes with biorefinery size, ethanol conversion rate and switchgrass yield. For instance, with 2 million gallons annual capacity, 95 gallons per ton ethanol conversion rate and 3 tons per acre of switchgrass yield, 7,018 acres of land should be contracted; with a 30 million gallons annual demand, 75 gallons per ton ethanol conversion rate and 5 tons per acre of switchgrass yield, 80,000 acres of land should be contracted. Currently, The University of Tennessee has contracted with 16 farmers to produce 720 acres of switchgrass in 2008, escalating to 6,000 acres by 2010 (Garland 2009). Given the scheduled opening of the pilot-scale biorefinery in East Tennessee, research is needed to determine the potential draw area of feedstock for different plant size and the cost minimizing harvest and storage methods considering dry matter losses.

Thus, the objective of this paper is to determine the acreage in each region to participate in the switchgrass production, the optimal combination of harvest and storage methods in each region, the schedule to transport switchgrass to the biorefinery to maintain a steady monthly supply of switchgrass to the biorefinery while minimizing the logistic costs to deliver switchgrass to the biorefinery.

Conceptual Framework

For the 10 county feedstock draw region in East Tennessee, it is assumed that the biorefinery contracts with individual farmers and pays for opportunity cost of land, switchgrass establishment, annual maintenance, harvest and storage. The biorefinery is responsible for transportation and the arrangement of the schedule for switchgrass harvest, storage and transportation. The objective of the biorefinery is to minimize the delivered cost of switchgrass which includes the contract price paid to the farmers for switchgrass production and cost associated with switchgrass transportation under constraints related to the farm quantity supplied, processor's capacity, outside demand, and other logical considerations. The annual delivered cost is comprised of three major components: 1) the dry matter loss adjusted post storage cost for switchgrass that is delivered to the biorefinery after a period of storage, 2) the post storage cost for switchgrass that is delivered to the biorefinery immediately after harvest, and 3) the transportation cost for all switchgrass that is delivered to the biorefinery over a one year time frame. There are four sets of constraints related to harvest, storage, transportation and plant capacity. First, there are seven constraints at harvest. Land used to grow switchgrass should not exceed the cropland available for the third major crop in each region (English 2009). Acres contracted in each soil each county should not exceed the acres that available on that soil on that county. The total switchgrass tonnage harvested should not be more than the total yields from each region. The harvest window is from November to February (English 2009). The available machine time should not exceed the available field hours in each month. The net harvest should be no less than zero. In another words, the tonnage of switchgrass that is transported immediately after harvest should not be greater than the tonnage that is actually harvested during the same month. The total machine time each month should not exceed the field hours available in each month. There are six constraints during storage and transportation. No switchgrass is stored in November initially. Switchgrass that is stored in the next month should not be greater than the switchgrass that is stored in the current month less the dry matter loss during storage, minus the switchgrass tonnage that is transported to the biorefinery from storage, and plus the net harvest in the next month. The switchgrass that is transported from storage should not exceed the switchgrass that is available in storage in any month. The newly stored switchgrass should not exceed the difference of the newly harvested switchgrass and the switchgrass that is transported to the biorefinery immediately after harvest. There are three constraints at the plant. The switchgrass that is delivered to the processing plant each month should not exceed the capacity of the plant. The ethanol produced from the biorefinery should meet the monthly demand for the biorefinery. All the parameters and variables in the model are not negative. Finally, losses for harvest and transportation are assumed to be zero in this model.

The plant's objective function can be represented by:

$$
\begin{aligned}
&Min. \\
&Cost = \sum_{m=1}^{12}\sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{b=1}^{B}\sum_{t=1}^{T}\sum_{c=1}^{C}\left(\frac{\dfrac{land_{sb}+est+amc+\sigma_{sb}}{y_{sb}}\times XTO_{isbtcm}+\gamma_{btc}\times XTO_{isbtcm}}{1-cv_{btcm}}\right) \\
&+\sum_{m=1}^{12}\sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{b=1}^{B}\left(\frac{land_{sb}+est+amc+\sigma_{sb}}{y_{sb}}\times XTN_{isbm}\right) \\
&+\sum_{m=1}^{12}\sum_{i=1}^{I}\sum_{b=1}^{B}\theta_{ib}\times\left(\sum_{t=1}^{T}\sum_{c=1}^{C}XTO_{ibtcm}+\sum_{t=1}^{S}XTN_{ibsm}\right)
\end{aligned}
\tag{1}
$$

Subject to:

Harvest

$$\sum_{b=1}^{B}\sum_{s=1}^{S}A_{isb} \le p\times\sum_{s=1}^{S}aa_{is} \qquad \forall\cdot i \quad (2)$$

$$\sum_{b=1}^{B}A_{isb} \le aa_{is} \qquad \forall\cdot i,s \quad (3)$$

$$\sum_{m=1}^{12}XH_{isbm} \le y_s\times A_{isb} \qquad \forall\cdot i,s \quad (4)$$

$$XH_{isbm} \le y_s\times AH_{isbm} \qquad \forall\cdot i,s,b,m \quad (5)$$

$$XH_{isbm} = 0 \qquad m \geq March \quad (6)$$

$$XH_{isbm} \geq XTN_{isbm} \qquad Feb \geq m \geq Nov \quad (7)$$

$$\sum_{i=1}^{I}\sum_{s=1}^{S} mtb_{sb} \times AH_{isbm} \leq Numb_{mb} \times avehour_{m} \qquad \forall \cdot m,b \quad (8)$$

Storage and Transport

$$XTO_{isbtcm} = 0 \qquad m = Nov \ \& \forall \cdot i,s,b,t,c,m \quad (9)$$

$$\sum_{t=1}^{T}\sum_{c=1}^{C} XSN_{isbtcm} = XH_{isbm} - XTN_{isbm} \qquad m = Nov \ \ \& \forall \cdot i,s,b \quad (10)$$

$$\sum_{t=1}^{T}\sum_{c=1}^{C} XS_{isbtcm+1} = \sum_{t=1}^{T}\sum_{c=1}^{C} [(1-\upsilon_{btcm}) XS_{isbtcm} - XTO_{isbtcm}] + XH_{isbm+1} - XTN_{isbm+1} \qquad \forall \cdot i,s,b,m \quad (11)$$

$$XSN_{isbtcm} = XS_{isbtcm+1} - (1-\upsilon_{btcm}) XS_{isbtcm} + XTO_{isbtcm} \qquad \forall \cdot i,s,b,t,c,m \quad (12)$$

$$(1-\upsilon_{btcm}) XS_{isbtcm} \geq XTO_{isbtcm+1} \qquad m = Feb \ \& \forall \cdot i,s,b,t,c \quad (13)$$

$$(1-\upsilon_{btcm}) XS_{isbtcm} \geq XS_{isbtcm+1} \qquad m = Feb \ \& \forall \cdot i,s,b,t,c \quad (14)$$

Processing plant

$$cap_{m} \geq \lambda \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{s=1}^{S} (\sum_{t=1}^{T}\sum_{c=1}^{C} XTO_{isbtcm} + XTN_{isbm}) \qquad \forall \cdot m \quad (15)$$

$$Q_{m} = \lambda \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{s=1}^{S} (\sum_{t=1}^{T}\sum_{c=1}^{C} XTO_{isbtcm} + XTN_{isbm}) \qquad \forall \cdot m \quad (16)$$

$$Q_{m} \geq d_{m} \qquad \forall \cdot m \quad (17)$$

Variables:

A: acres of switchgrass harvested annually

AH: acres of switchgrass harvested through November to February

XH: tons of switchgrass harvested through November to February

XS: tons of switchgrass stored through November to October

XSN: tons of switchgrass put into storage through November to February

XTN: tons of switchgrass transported immediately after harvest through November to February

XTO: tons of switchgrass transported from storage through November to October

Q: quantity of ethanol produced in each month

Numb: number of equipment used in harvest

Parameters:

land: opportunity cost of land

est: amortized establishment costs

amc: annual maintenance costs

σ*: harvest cost per acre*

γ*: storage cost per ton*

ν*: monthly storage loss*

cv: cumulative storage loss

θ*: transport cost per ton*

y: switchgrass yield

p: percentage of total cropland available to switchgrass across counties

λ*: conversion rate to ethanol*

d: monthly demand of ethanol

aa: cropland available on soil s in county i

cap: capacity of the biorefinery

mtb: machine time per acre for one machine

avehour: average working hours in each month for each equipment

Subscripts:

m: month

i: production region (county)

s: soil type

b: harvest method (round baler, square baler)

t: storage cover type (no cover, tarp)

c: storage surface type (bare ground, gravel, pallet)

Data and Methods

Switchgrass harvest and storage experiment design

Storage loss data for different bale types and storage treatments were obtained from an ongoing research experiment by English, Larson and Tyler (2009). The three treatments in the study are bale harvest method, bale storage method and bale storage time. Large round bales (5 ft ×4 ft) and large rectangular bales (4 ft × 8 ft) were the two bale harvest treatments. Bale storage treatments in the experiment including covering or not covering the round and rectangular bales with a protective tarp on one of three storage surfaces: 1) well-drained ground, 2) a gravel surface, or 3) a wooden pallet. For the large round bales, the six storage treatments are: 1) uncovered on well-drained ground 2) uncovered on gravel, 3) uncovered on wooden pallets, 4) covered on well-drained ground, 5) covered on gravel, and 6) and covered on wooden pallets. For the rectangular bales, the four storage treatments are: 1) uncovered on gravel, 2) uncovered on wooden pallets, 3) covered on gravel, and 4) and covered on wooden pallets. The target bale storage times in the experiment that were used in this analysis were: 1) 0 days and 2) 200 days.

Savoie et al. (2006) found that dry matter loss of corn silage can be expressed by an exponential function of time *t* shown below:

$$L = L_{\max} - (L_{\max} - L_{\min}) \times (-kt)^{e}, \tag{18}$$

Where L is the predicted dry matter loss, L_{max} is the maximum dry matter loss, L_{min} is the minimum dry matter loss, k is the dry matter loss parameter, and e is the natural log. The decreasing exponential model for the dry matter loss over time assumes that when there is no organic matter to be oxidized, the dry matter loss would stop at some time. This equation was used to estimate the monthly dry matter losses for switchgrass bales. The storage loss data for switchgrass bales that stored for 200 days for t = 6.57 ($200/365 \times 12$) were obtained from English, Larson and Tyler (2009). The maximum dry matter loss L_{max} was assumed to be 100% and the minimum dry matter loss L_{min} to be 0% for simplicity (Savoie et al. 2006). $L_{6.57}$, L_{max}, L_{min} and $t = 6.57$ were used to estimate the loss parameter k, which depends on density, depth and cover (Savoie et al., 2006). There were 10 dry matter loss parameters which correspond to 6 storage treatments for round bales and 4 storage treatments for rectangular bales in the experiment design (English, Larson and Tyler 2009). These storage loss parameters and 12 monthly time intervals were used to estimate the average dry matter loss in each month.

Switchgrass yields

The soil types, nitrogen rates and local weather conditions were the most important determinants for switchgrass yields. The total cropland acreage in each study county was determined using the 2007 Census of Agriculture County profile (U.S. Department of

Agriculture, Natural Resource Conservation Service 2007). A total of 130 soil types used in cropland, hayland and pasture were identified in the study area (U.S. Department of Agriculture, Natural Resource Conservation Service 2009). Soils that were < 0.1 percent of the total available acres were excluded, leaving 77 soil types. The acreage of land available on each soil type in each region for switchgrass was estimated using these data. Fertilizer levels used to simulate switchgrass yields on each soil type came from switchgrass annual production budget published by The University of Tennessee Extension (Gerloff 2008). Weather data were obtained from the local weather station (U.S. Department of Commerce, Natural Ocean and Atmosphere Administration 2008). Switchgrass yields were simulated using the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al. 1996). Inputting the soil types, the nitrogen rate and the latitude and longitude of the center in each county in the ALMANAC model, switchgrass yields for 77 soil types in East Tennessee were simulated.

Enterprise budgeting

The delivered costs to the plant include the opportunity cost on land, the establishment costs incurred in the first year of production, the recurring annual costs for nutrients, pest control, harvest, storage, and transportation. The costs of equipment assumed to be used in the establishment, maintenance, harvest, storage and transportation of switchgrass is presented in Table 1 (All tables and figures are shown in Appendix). The equipment assumed for the round baling system included a 5 ft × 4 ft large round baler, a mower, a rake, and a loader and a tractor. The rectangular baling system differed from the round baling system by replacing the large round baler with a 4 ft × 8 ft rectangular baler. After harvested, all the switchgrass bales were transported by a tractor to the field edge and stored with or without tarps on bare ground, gravel or pallets. Semi-tractor trailers were assumed for switchgrass bale transportation from the farm to the biorefinery. Enterprise budgeting was employed to calculate the costs for each budget in accordance with the American Agricultural Economics Association Cost and Return Handbook (AAEA 2000) and American Society of Agricultural Engineers (ASAE) Standards (2000). Labor time was assumed to be 1.25 times the corresponding machine time (ASAE Standard 2000) and the wage for each operation was assumed to be $8.5/hour (Georlof 2008).

(1) Pre-harvest cost (land, est and amc)

The 77 soil types were sorted into two primarily cropland and primarily pasture land and hay land groups (*z*) based on the soil series descriptions from U.S. Department of Agriculture, Natural Resource Conservation Service (U.S. Department of Agriculture, Natural Resource Conservation Service 2009). Group average land rental rates were assumed to be $20/acre and $60/acre for pasture group and crop group in accordance with the Agricultural Land Values and Cash Rents for Tennessee reported by the Tennessee Department of Agriculture through 2003 to 2008 (Tennessee Department of Agriculture 2008). Land rental rates in each group were indexed by the following formula:

$$land_s = \frac{rate_z}{\bar{y}_z} \times y_s, \qquad (19)$$

Where $rate_z$ is the rental rate on land group *z*, $\bar{y}_z$ is the mean yield for land group *z*, and y_s is switchgrass yield for soil type *s*. Establishment cost was amortized over 5 years based on the assumption of a potential contract period of 5 years (Garland 2009) (Table 2). Annual maintenance cost includes costs of fertilizer and pesticides (Table 3).

(2) Harvest cost (σ)

The cost of equipment per acre is the product of corresponding cost per hour obtained from enterprise budgeting and machine time of the equipment (Table 1). The total harvest cost per acre is the sum of the per acre costs of mowing, raking, baling and staging. Machine time of the round balers is assumed to be linearly related to yield based on a throughput capacity of 5.5 dry tons per hour for switchgrass (Mooney et al. 2008). The machine times for mowing and raking were assumed not to vary with yield. Dry matter losses during harvest were assumed to be zero in this study.

(3) Storage cost (γ)

The estimated costs for plastic tarps, gravel, and wooden pallets used for storing switchgrass bales were obtained from an informal survey from suppliers in Tennessee. Collins et al. (1997) found that 3-2-1 pyramid design with three bales in the bottom, two in the middle and one on the top is practical and effective to shed water in the high rainfall, humid subtropical climate found in Tennessee and the southeast United States. A 25 ft by 54 ft tarp was the assumed size used to cover both round and rectangular bales. Given the round bale size of 5 ft by 4 ft and the rectangular bale size of 4 ft by 8 ft, up to seventy-two round bales or sixty rectangular bales can be stored under one such tarp. A gravel pad with a 5-inch depth was assumed as a base for placing bales. Thus, one ton of gravel was assumed to cover 32 sq ft on the ground and an average of three round bales or 2.5 rectangular bales can be placed in that area when a 3-2-1 pyramid is assumed. Three pallets were assumed for six round bales placed in one row of the 3-2-1 pyramid design. Four pallets were assumed needed for one row with five rectangular bales. Given the expected contract period of 5 years, the tarps, gravel and pallets were assumed to have 5 years of useful life. Thus, the costs of tarps, gravel and pallets were amortized over 5 years and assumed to have zero salvage value. Wooden pallets were assumed to be replaced at a rate of 20 percent per year. Tarps and gravel pads were assumed to have a replacement rate of 1 percent of initial cost for each year of use. The storage cost per ton (γ_{sh}^{0}) is sum of costs of the top cover, the bottom support, labor and pickup truck.

(4) Transportation cost (θ)

The cost per hour of the semi-tractor trailer was obtained using the same budget procedures as used for harvest. The distance to the plant for switchgrass delivery is assumed to be the distance from the center of a candidate county to Vonore in Monroe County. The average travel speed of the semi-tractor trailer was assumed to be 50 miles/hour (Brechbill, Tyner, and Ileleji 2008). The capacity of the trailer was assumed to be 36 large round bales or 24 rectangular bales. Thus, the trailer carries 13 round bales or 6.5 rectangular bales per hour. The average bale density was assumed to be 0.4 tons/bale for the round bales and 1 tons/bale for the rectangular bales, so on average the trailer carries 13 tons of round bales per hour or 16 tons of rectangular bales per hour. Finally, the cost per ton of transportation (θ_{hst}^{0}) was obtained by dividing the cost per hour by tons per hour the trailer carries. Dry matter loss during transportation was assumed to be 2 percent for round bales and rectangular bales (Kumar and Sokhansanj 2006).

Monthly working hours

The harvest period for switchgrass was assumed to be through November to February. Factors that may limit the number of hours of harvest available during this period include low temperatures, shorter days with less available sunlight, and precipitation. Thus, the following methods and data were used to limit the total hours available for harvest in the mixed integer programming model. First, the average numbers of days of precipitation of < 0.01 inch precipitation in each month for Knoxville, TN, were used to estimate the average numbers of field days in each moth of harvest (University of Utah 2008). Second, because biomass in the field may need time after a precipitation event to dry out before harvest, 70 percent of the field days were assumed to be available for harvest. Finally, it is assumed that six hours of each available field day were usable for field operations. Thus, the total numbers of hours available for harvest in the model were influenced not only by available harvest hours but by baler type and switchgrass yields. For example, a rectangular baler with the assumed throughput of 12 dt/hour could cover 636 acres during the harvest season assuming 6 dt/acre switchgrass yield. By comparison, a round baler with an average throughput of 5.5 dt/hour could only cover 292 acres in a season.

Analysis

Fourteen scenarios differentiated by plant size, bale type, whether dry matter loss during storage is considered, land area covered by harvest equipment, and whether available equipment were restricted were evaluated in the analysis (Table 8). For the base scenario, annual biorefinery capacity was assumed to be 2 million gallons per year, the plant could process more than one bale type, dry matter losses during storage were considered for each harvest and storage treatment, the rectangular baler was assumed to harvest 100 acres of land per year (the same as the round baler), and there is no limit on the availability of the balers. Additional twelve scenarios involving 25 million and 50 million gallon per year plant capacity, round or rectangular baler only, dry matter loss during storage considered or not considered and size economies with the rectangular baler were also analyzed. The scenarios with and without dry matter losses during storage were used to evaluate how dry matter losses impact the cost of feedstock at plant gate. Increasing the area a rectangular baler could cover in a harvest season from 100 acres to 500 acres was used to look at the impact that the potential size economies of a rectangular baler would have on the cost of delivered feedstock. Finally, a limitation on available harvest equipment was imposed to evaluate how the harvest and delivery schedule would change from the other scenarios where the number of equipment was not limited. It was assumed that 250 round balers and 50 rectangular balers are available in each harvest month for a plant with an annual capacity of 50 million gallons per year.

Results

Base scenario (scenario 1)

The soil types and land area selected by county, the monthly amount of switchgrass that is harvested, the amount of switchgrass stored and transported to the biorefinery each month along with the optimal harvest and storage methods are shown in Tables 4 to 7 for the base scenario. Results indicate that soil types with higher yields of switchgrass and with shorter distances from the biorefinery were chosen first in the model. The selected soil types were Bellamy, Claiborne, Santeetlah, Staser, Toxaway and Tusquitee and had an average switchgrass yield of 7.64 dt/acre. The counties producing switchgrass under the base scenario were Blount, McMinn, Monroe and Polk and had an average distance of 20 miles to the biorefinery. From November to January, switchgrass was harvested only by rectangular balers and transported to the plant immediately after harvest. In February, both round and rectangular bales of switchgrass were harvested, but only rectangular bales were transported to the plant. The round bales of switchrass were put into storage using tarps and pallets or without any protection. For March through April, the round bales stored without protection were transported to the biorefinery. During the following months of the year, the round bales stored with tarps and pallets were transported to the biorefinery. Given an annual demand of 2 million gallons of ethanol from the biorefinery, the biorefinery would pay $0.73/gallon on average for switchgrass feedstock delivered to the plant gate when mixed bale types and dry matter loss during storage were considered. Assuming no constraints on available harvest equipment and balers cover an average of 100 acres of land per year, 38 round balers, 8 rectangular balers, 51 loaders, 11 mowers, 8 rakes, 112 tractors were needed to harvest 2,872 acres of land with an initial investment on equipment of $18,069,600 in the base model.

Sensitivity analysis (Table 8)

(1) Plant size (scenarios 1-3)

The small scale biorefinery was assumed to be expandable to an annual capacity of 50 million gallons of ethanol. Assuming all other variables were set at their base scenario values, the average delivered cost rose by $0.06/gallon to $0.79/gallon of ethanol produced as the plant capacity was increased from 2 million to 25 million gallons of ethanol annually. The planted area of switchgrass required increased from 2,872 to 43,980 acres. When the plant size was increased from 25 million to 50 million gallons of ethanol, the rise in delivered cost was $0.02/gallon to $0.81/gallon of ethanol produced. Planted area of switchgrass more than doubled to 93,261 acres when compared to the 25 million gallon per year plant size. As the plant size was expanded, the delivered cost at plant gate was increased, but at a decreasing rate. Also, when the plant size was small, the more productive land located near the biorefinery was chosen first in the model. As the plant size was expanded, the less productive soil types located further away from the biorefinery came into the solution as well. The less productive land had smaller average yields and thus the fixed costs of production were spread over a smaller harvested tonnage. Thus, as the plant capacity was increased, the delivered cost per dry ton of biomass also rose in the model.

(2) Bale type and plant size (scenarios 4-9)

Bale type may also influence the cost at plant gate. When the plant size was assumed to be 2 million gallons of ethanol annually, the delivered cost was $0.75/gallon and $0.78/gallon of ethanol produced in the round baling only and the rectangular baling only models, respectively. When the plant size was expanded to 25 million gallons of ethanol annually, the delivered cost increased by $0.05/gallon and $0.07/gallon of ethanol produced in the round baling only and the rectangular baling only models, respectively. As the plant size was enlarged from 25 million to 50 million gallons of ethanol, the delivered cost was increased by $0.02/gallon of ethanol produced in both the round baling only and the rectangular baling only models, respectively. Given the same plant size, the harvest area was smaller for the round only baling system than the rectangular only baling system. This was primarily due to smaller dry matter losses during storage for covered round balers compared with covered rectangular bales. Smaller dry matter losses during storage with round bales decreased the amount of switchgrass area required for the biorefinery. Even though the round only baling system beats the rectangular only system in terms of delivered feedstock cost on which the production cost of ethanol depends, the production cost of ethanol depends on ethanol processing cost as well. Differences in processing costs were not considered once the biomass is at the plant for different bale types in this analysis. Further research on the processing cost of different forms of the biomass may reveal the superiority of the form of biomass delivered and processed.

(3) Rectangular baler capacity (scenario 3 vs. 10)

When the rectangular baler capacity was increased from 100 acres/year to 500 acres/year, the delivered cost at plant gate was decreased from $0.81/gallon to $0.68/gallon or by 16 percent. The total acreage contracted was increased from 93,261 to 98,457 and the tonnage harvested each year was increased from 561,358 to 590,009 acres. Because rectangular baler harvest costs declined relative to round baler costs, more of the land area was harvested using rectangular baler which resulted in larger dry matter losses during storage. The larger storage losses caused more switchgrass to be planted in the model to compensate for higher storage losses under the 500 acres per year harvest scenario.

(4) Dry matter loss during storage (scenario 3 vs. 12)

When storage loss was not considered, the delivered cost at plant gate was decreased from $0.81/gallon to $0.80/gallon or by 1 percent. The total acreage contracted, tonnage harvested and the total delivered costs do not change significantly. Dry matter losses for round bales stored using tarps and pallets were much lower than other methods in the model which explains the small difference in costs.

(5) Rectangular baler capacity and dry matter loss during storage (scenario 3 and 11)

When rectangular baler annual capacity was assumed to be 500 acres/year and dry matter loss during storage were not considered, the delivered cost at plant gate was decreased from $0.81/gallon to $0.64/gallon or by 21 percent. This cost reduction is much higher when both factors are considered together rather than separately as was done under scenario 10 and 12. The results imply that the rectangular baler capacity and dry matter loss during storage together have more influence on the delivered cost at plant gate than the sum of the effects of the individuals on the delivered cost at plant gate.

(6) Availability of the balers (scenario 3 vs. 13, and 10 vs. 14)

Compared with scenario 3, when the number of round balers was limited to 250 and the number of rectangular balers was limited to 50 in each harvest month, the delivered cost at plant gate didn’t change. However, when the rectangular baler capacity was assumed to be 500 acres/year, the limit on the availability of balers increased the delivered cost at plant gate from $0.68/gallon to $0.75/gallon.

Sensitivity to percentage of land available for switchgrass production

The amount of land available for switchgrass production is the primary resource constraint in the model. The marginal value of land in each county was estimated when the plant size was assumed to be 50 million gallons of ethanol per year. On average, if an additional acre of land is available in Monroe or Polk County, the total annual delivered cost to the biorefinery was reduced by $19.70 and $9.40 respectively. Thus, the marginal value of land was relatively small. The marginal value of land depends on the productivity of the land and the distance of the land for the biorefinery. For example, on Santeetlah soil (with average switchgrass yield 8 dt/acre), the marginal value of land averages $49. It implies that if an additional acre of Santeetlah land was available, the annual delivered cost would decrease by $49. Given the land constraints in the model, it appears that the land area available for switchgrass is large enough to support a plant with a capacity of 50 million gallons of ethanol per year. However, changing the percentage of land available for switchgrass production in the study area from 33.6 percent to 22 percent for a plant capacity of 50 million gallons of ethanol per year resulted in a $0.66 million increase in the cost of delivered feedstock. If less than 22 percent of the total land area in the potential feedstock draw area was available for switchgrass production, the model solution is infeasible, indicating that the plant could not obtain enough feedstock to run at a full capacity of 50 million gallons per year.

Summary and Conclusions

A pilot biorefinery for processing switchgrass into ethanol is being planned for East Tennessee. To maintain a steady supply flow of switchgrass, the biorefinery needs a detailed annual schedule to harvest, store and transport switchgrass to the processing plant. Thus, a mixed integer mathematical programming model was developed to determine optimal solutions for scheduling switchgrass harvest, storage and transportation for a biorefinery in East Tennessee. The potential feedstock draw area for this analysis included Blount, Bradley, Knox, Loudon, McMinn, Monroe, Polk, Rhea and Roane Counties. For the 2 million gallon per year biorefinery capacity scenario, the four counties of Blount, McMinn, Monroe and Polk with 2,872 acres of land were selected. The land chosen in the model under this plant size scenario is characterized as productive and close to the biorefinery. The model results indicated that newly harvested rectangular bales would be delivered to the biorefinery immediately, round bales would be put into storage without protection if delivered in March and April or with tarp and pallet protection if delivered later in the year. Under this scenario, the cost of the switchgrass feedstock delivered to the plant gate averages $0.73/gallon of ethanol produced by the biorefinery.

The delivered cost of switchgrass is sensitive to plant size, bale type, storage loss, the number of acres a rectangular baler can cover annually and availability of balers. When the plant size was enlarged to 25 million gallons of ethanol capacity, the nine counties of Blount, McMinn, Monroe, Polk, Bradley, Loudon, Meigs, Rhea and Roane with 43,980 acres of land were selected by the model. Less productive land such as Allen soil (with average switchgrass yield of 5.32 dt/acre) in Blount County and productive land further away from the plant such as in Bradley County (with average distance of 41.3 miles to the biorefinery) were chosen. As the plant size was expanded to 50 million gallons of ethanol per year, less productive lands further away from the biorefinery were chosen to meet the annual ethanol demand. Assuming a limitation on available harvest equipment from November to January, rectangular bales were preferred regardless of the plant size. In February, both rectangular bales and round bales were harvested, but rectangular bales were transported directly to the biorefinery. The round bales harvested in February were put into storage without protection if scheduled for earlier delivery or with tarp and pallet protection if scheduled for later delivery.

Results also indicate that the annual delivered cost of the rectangular baling only system was higher than that of the round baling only system due to larger storage losses with the rectangular baling system. As the plant size was increased, the annual delivered cost increased faster using the rectangular baling only system than with the round baling only system. However, delivered costs were lower for a mixed bale type system than a single bale type system. When storage losses were not considered, the cost of feedstock was decreased by only $0.01/gallon or 1.2 percent of ethanol produced by a plant with a capacity of 50 million gallons of ethanol per year. Round bales stored with tarps and pallets provided much lower storage dry matter losses than the other bale storage protection in this analysis. If a rectangular baler was able to cover 500 acres rather than 100 acres of land per year, the delivered cost was $0.13/gallon (16 percent) lower for feedstock at the plant gate when a capacity of 50 million gallons of ethanol per year was assumed. In general, the feedstock cost in terms of ethanol produced in this study was substantially higher than The U.S. Department of Energy's National Renewable Energy Laboratory's goal for feedstock production by 2012, which is 0.39/gallon (Pacheco, 2006).

In sum, the availability of the equipment, and the efficiency of the equipment, especially the machines such as rectangular baler used in harvest, interacts with the storage loss, affecting the annual delivered cost of switchgrass. Less expensive and more efficient equipment and better storage protection lowered the delivered cost significantly in the model. The feedstock harvest and delivery process is an equipment intensive enterprise since the cost on equipment accounts for a large proportion of the annual feedstock delivered cost.

There are several limitations in this analysis. Pre-processing and processing costs once the feedstock was delivered were not included in this analysis. Given that the biorefiney's profit equals the revenue from selling ethanol minus the cost from producing ethanol, the processing cost is an important factor in determining the cost of ethanol production. Further study on the benefits and costs on pre-processing and processing activities may disclose more information on the feasibility of using switchgrass as a bioenergy crop.

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Appendix

Table 2.1 Machinery Equipment Costs for Switchgrass in East Tennessee

Cost of Item	Drill	Sprayer	Round Baler	Rectangular Baler	Mower	Rake	Front End Loader	Tractor 215HP Round	Tractor 215HP Rectangular	Pickup Truck	Semi-Tractor
Basic Parameters											
Purchase Price[a] ($)	17,000	8,400	23,000	87,700	6,500	3,000	7,500	143,000		25,000	120,000
Hours of Useful Life[a] (hours)	1,500	1,500	1,500	3,000	2,000	2,500	1,000	12,000		12,000	22,000
Hours of Use Per Year[b] (hours/year)	100	100	90.91	41.67	23.57	15.28	55.00	184.76	135.52	300	1,000
Fuel Price[d] ($/gallon)	1.83	1.83	1.83	1.83	1.83	1.83	1.83	1.83		1.83	1.83
Fuel Use[b] (gallon/hour)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.42		2.00	22.12
Lubrication Factor[c] (%)	15.00%	15.00%	15.00%	15.00%	15.00%	15.00%	15.00%	15.00%		15.00%	15.00%
Interest Rate[c] (%)	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%	3.00%		3.00%	3.00%
Housing % of PP[c]	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%		0.75%	0.75%
Tax Rate % of PP[c]	1%	1%	1%	1%	1%	1%	1%	1%		1%	1%
Insurance % of PP[c]	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%		0.25%	0.25%
Useful Years	15.00	15.00	7.14	30.00	15.04	20.83	10.00	18.02		18.00	22.00
Salvage Value ($)	1,700	840	9,137	9,083	1,874	711	2,707	30,061		2,500	18,171
Ownership Costs ($/hour)	18.70	9.24	21.97	113.77	14.51	9.86	10.92	42.69	55.18	5.70	9.33
Capital Recovery ($/hour)	13.60	6.72	16.91	71.68	8.99	5.94	8.20	27.21	34.07	0.14	6.93
TIH ($/hour)	5.10	2.52	5.06	42.10	5.52	3.93	2.73	15.48	21.10	7.73	2.4
Operating Costs ($/hour)	8.50	3.92	16.09	24.85	5.71	0.87	4.06	33.95		17.83	68.29
Diesel Fuel ($/hour)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.23		6.30	40.48
Lubrication Costs ($/hour)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.58		0.95	6.07
Repair ($/hour)	8.50	3.92	16.09	24.85	5.71	0.87	4.06	14.13		2.08	21.74
Total Machinery Cost ($/hour)	27.20	13.16	38.07	138.62	20.22	10.73	14.98	76.64	89.13	25.20	77.63

[a] Gerloff, 2008 except for the price of rectangular baler

[b] Based on assumed harvest acre of 100 per year for the harvest equipment compliment

[c] Calculated from Agricultural and Applied Economics Association and American Society of Agriculture Engineers Standards (AAEA and ASAE), 2000

[d] AAEA and ASAE, 2000

[e] Average simulated value from @risk based on the price report in Agricultural Statistics from 1977 to 2005 (USDA-NASS).

Table 2.2 Establishment Budget for Switchgrass in East Tennessee

Cost of Item	Unit	Quantity	Unit Price	Establishment Costs
Variable Expenses[a]				
Seed	Lbs/Acre PLS	*75*	$20.00	$150.00
Herbicide				
Roundup Original Mix	Pt/Acre	3.2	$2.24	$7.17
Cimarron	Oz/Acre	0.1	$19.00	1.9
Grass herbicide	App/Acre	3	$7.00	$21.00
Operating Capital	%	*Varies*	8	$7.83
Machinery Expenses[b]				
Diesel Fuel	Gal/Ac	4.17	$1.83	$10.11
Repair and Maintenance	Acre	1	$9.79	$9.79
Depreciation	Acre	1	$9.01	$9.01
Labor Expenses[a]				
Operator Labor	Hrs/Acre	0.62	$8.50	$10.39
Total Establishment Cost	$/Acre			$229.87
Amortized Establishment Cost	$/Acre/Year			$51.33

[a] Gerloff, 2008
[b] Calculated from AAEA and ASAE standards

Table 2.3 Annual Maintenance Budget for Switchgrass in East Tennessee

Cost of Item	Unit	Unit Price	Quantity	Production Costs
Variable Expenses				
Fertilizer				
Nitrogen	Lbs/Acre	$0.42	*60*	$25.20
Herbicide				
Cimarron	Oz/Acre	$19.00	0.1	$1.90
Grass herbicide	Aplic/Acre	$7.00	1	$7.00
Operating Capital	%	8		$1.46
Machinery Expenses				
Diesel Fuel	Gal/Acre	$1.83	*Varies*	$1.39
Repair and Maintenance	Acre	*Varies*	1	$1.17
Depreciation	Acre	*Varies*	1	$0.31
Labor Expenses				
Operator Labor	Hr/Acre	$8.50	3.93	$1.06
Total Annual Maintenance Cost	$/Ac			$40.66

[a] Gerloff, 2008
[b] Calculated from AAEA and ASAE standards

Table 2.4 Land acre contracted on soil type *s* in county *i* in the base scenario[a]

Soil type	*County*			
	Blount	McMinn	Monroe	Polk
Bellamy	*NA*		86	*NA*
Claiborne			396	*NA*
Santeetlah	150	*NA*	*NA*	
Staser		157	*NA*	*NA*
Toxaway	*NA*	*NA*	117	554
Tusquitee		*NA*	1,412	
Total Acre	150	157	1,911	554

[a] In the base scenario, plant size is assumed to be 2 million gallons per year, the plant can process both round and rectangular bales, dry matter losses during storage are considered, and both the round and rectangular baler cover 100 acres of land in a harvest season.

Table 2.5 Harvest schedule for switchgrass from November to February in the base scenario[a]

Month	*County*	*Soil type*	*SWTG*		*Harvest Method*	
			acres	tons	Round	Rectangular
November	McMinn	Staser	157	*1237*		*
	Polk	Toxaway	60	*615*		*
December	Polk	Toxaway	180	*1,852*		*
January	Polk	Toxaway	180	*1,852*		*
February	Blount	Santeetlah	91	*726*	*	
	Blount	Santeetlah	59	*475*		*
	Monroe	Bellamy	86	*533*	*	
		Claiborne	396	*2,503*	*	
		Toxaway	117	*1,203*	*	
		Tusquitee	1,412	*10,082*	*	
	Polk	Toxaway	134	*1,377*		*

[a] In the base scenario, plant size is assumed to be 2 million gallons per year, the plant can process both round and rectangular bales, dry matter losses during storage are considered, and both the round and rectangular baler cover 100 acres of land in a harvest season.

Table 2.6 Arrangement for newly harvested switchgrass from November to February in the base scenario[a]

Activity	*Month*	*County*							*Shape*	
		Blount	McMinn	Monroe				Polk	Round	Rectangular
Immediate Delivery										
	November		*1,237*					*615*		*
	December							*1,852*		*
	January							*1,852*		*
	February	*475*						*1,377*		*
Storage with										
	February	*Santeetlah*[b]	*Staser*	*Bellamy*	*Claiborne*	*Toxaway*[b]	*Tuesquitee*	*Toxaway*		
Non-tarp + ground		*726*			*1,885*	*1,203*			*	
Tarp+pallet				*533*	*618*		*10,082*		*	

[a] In the base scenario, plant size is assumed to be 2 million gallons per year, the plant can process both round and rectangular bales, dry matter losses during storage are considered, and both the round and rectangular baler cover 100 acres of land in a harvest season.
[b] Soil types.

Table 2.7 Delivery schedule for stored switchgrass in the base scenario[a]

County	Blount					Monroe				
Month	Shape		Storage Method		Tons	Shape		Storage Method		Tons
	Round	Rectangular	Top	Bottom	Transported	Round	Rectangular	Top	Bottom	Transported
March						*		Non-tarp	ground	*1,852*
April	*		Non-tarp	ground	*699*	*		Non-tarp	ground	*1,153*
May						*		Tarp	pallet	*1,852*
June						*		Tarp	pallet	*1,852*
July						*		Tarp	pallet	*1,852*
August						*		Tarp	pallet	*1,852*
September						*		Tarp	pallet	*1,852*
October						*		Tarp	pallet	*1,852*

[a] In the base scenario, plant size is assumed to be 2 million gallons per year, the plant can process both round and rectangular bales, dry matter losses during storage are considered, and both the round and rectangular baler cover 100 acres of land in a harvest season.

Table 2.8 Scenarios for base[a] and alternative[b] models

Scenario	Plant size (gallons/year)	Bale type	Dry matter loss during storage (Yes or No)	Rectangular baler capacity (acres/year)	Limited number of balers (Yes or No)
1	*2,000,000*[a]	mix[a]	Yes[a]	100[a]	No
2	*25,000,000*	mix	Yes	100	No
3	*50,000,000*	mix	Yes	100	No
4	2,000,000	*round*	Yes	100	No
5	25,000,000	*round*	Yes	100	No
6	50,000,000	*round*	Yes	100	No
7	2,000,000	*rectangular*	Yes	100	No
8	25,000,000	*rectangular*	Yes	100	No
9	50,000,000	*rectangular*	Yes	100	No
10	50,000,000	mix	Yes	*500*	No
11	50,000,000	mix	*No*	*500*	No
12	50,000,000	mix	*No*	100	No
13	*50,000,000*	mix	Yes	100	*Yes*
14	*50,000,000*	mix	Yes	500	*Yes*

[a] In the base scenario, plant size is assumed to be 2 million gallons per year, the plant can process both round and rectangular bales, dry matter losses during storage are considered, and both the round and rectangular baler cover 100 acres of land in a harvest season.
[b] Other scenarios except the base scenario shown in this tale are alternative scenarios.

Table 2.9 Sensitivity analysis of the total delivered costs in all scenarios

Scenario	Plant size (gallons/year)	Bale type	Dry matter loss during storage (Yes or No)	Rectangular baler capacity (acres)	Limited number of balers (Yes or No)	Acreage contracted (acres/year)	Tonnage harvested (tons/year)	Total delivered costs ($/year)	Cost at plant gate of Ethanol[a] ($/gallon)
1	*2,000,000*[b]	mix[b]	Yes[b]	100[b]	No	2,872	22,454	$1,467,014	$0.73
2	*25,000,000*	mix	Yes	100	No	43,980	280,679	$19,712,320	$0.79
3	*50,000,000*	mix	Yes	100	No	93,261	561,358	$40,528,920	$0.81
4	2,000,000	*round*	Yes	100	No	3,060	23,622	$1,497,426	$0.75
5	25,000,000	*round*	Yes	100	No	44,317	282,702	$20,034,050	$0.80
6	50,000,000	*round*	Yes	100	No	93,850	561,798	$41,112,830	$0.82
7	2,000,000	*rectangular*	Yes	100	No	2,889	23,624	$1,560,782	$0.78
8	25,000,000	*rectangular*	Yes	100	No	46,377	295,004	$21,156,180	$0.85
9	50,000,000	*rectangular*	Yes	100	No	98,124	590,009	$43,556,410	$0.87
10	50,000,000	mix	Yes	*500*	No	98,457	590,009	$34,121,370	$0.68
11	50,000,000	mix	*No*	*500*	No	92,935	555,556	$31,829,480	$0.64
12	50,000,000	mix	*No*	100	No	92,163	555,556	$40,134,070	$0.80
13	50,000,000	mix	Yes	100	*Yes*	93,470	562,535	$40,537,910	$0.81
14	50,000,000	mix	Yes	500	*Yes*	94,040	562,776	$37,664,320	$0.75

[a] Assuming a 90 gallon/ton switchgrass dry matter to ethanol conversion rate.
[b] In the base scenario, plant size is assumed to be 2 million gallons per year, the plant can process both round and rectangular bales, dry matter losses during storage are considered, and both the round and rectangular baler cover 100 acres of land in a harvest season.

Table 2.10 Number of machines used in harvest for all scenarios

Scenario	Plant size (gallons/year)	Bale type	Dry matter loss during Storage (Yes or No)	Rectangular baler capacity (acres)	Limited number of balers (Yes or No)	Round baler (#/year)	Rectangular baler (#/year)	Loader (#/year)	Mower (#/year)	Rake (#/year)	Tractor (#/year)	Initial Investment on Equipment ($/Life)
1	*2,000,000*[a]	mix[a]	Yes[a]	100[a]	No	38	8	51	11	8	112	$18,069,600
2	*25,000,000*	mix	Yes	100	No	475	98	629	143	89	1,435	$230,638,600
3	*50,000,000*	mix	Yes	100	No	950	194	1,261	303	188	2,896	$464,982,800
4	2,000,000	*round*	Yes	100	No	58	0	53	10	7	125	$19,692,500
5	25,000,000	*round*	Yes	100	No	592	0	623	142	90	1,559	$242,418,500
6	50,000,000	*round*	Yes	100	No	1,375	0	1,262	303	190	3,128	$490,933,500
7	2,000,000	*rectangular*	Yes	100	No	0	26	53	10	7	95	$16,348,700
8	25,000,000	*rectangular*	Yes	100	No	0	332	664	150	94	1,239	$212,530,400
9	50,000,000	*rectangular*	Yes	100	No	0	663	1,327	316	199	2,506	$429,106,600
10	50,000,000	mix	Yes	*500*	No	0	663	1,327	318	199	2,508	$429,405,600
11	50,000,000	mix	*No*	*500*	No	0	590	1,182	284	177	2,235	$382,590,000
12	50,000,000	mix	*No*	100	No	0	587	1,176	280	175	2,219	$379,961,900
13	50,000,000	mix	Yes	100	*Yes*	877	191	1,186	283	178	2,716	$436,578,200
14	50,000,000	mix	Yes	500	*Yes*	859	200	1,187	285	178	2,710	$436,116,000

[a] In the base scenario, plant size is assumed to be 2 million gallons per year, the plant can process both round and rectangular bales, dry matter losses during storage are considered, and both the round and rectangular baler cover 100 acres of land in a harvest season.

SUMMARY

Summary

This thesis analyzed the economic implications of establishing a biorefinery in Tennessee from both the farmers' and processing plant's perspectives. The biorefinery will be likely to contract with farmers for the switchgrass production. The first paper evaluated the cost of production from a farmer's perspective and included costs for switchgrass stand establishment, annual maintenance, harvest, storage and transportation in the analysis. For farmers that were contracted to deliver switchgrass immediately after harvest, rectangular bales minimized the delivered cost. But for farmers that were contracted to deliver switchgrass after 200 days in storage, round bales without storage protection minimized the delivered cost. Due to storage costs and losses, the delivered cost was increased by \$21.49/dt for switchgrass produced on more productive West Tennessee Loring soil which has an average switchgrass yield of 9 dt/acre, and \$25.67/dt for switchgrass produced on less productive East Tennessee Dandridge soil which has an average switchgrass yield of 5.7 dt/acre. The switchgrass yield along with the storage dry matter losses enlarged the difference on the delivered costs between different soils.

To maintain a steady supply of switchgrass, the biorefinery needs a delivery schedule for switchgrass harvest, storage and transportation. The second paper used a mixed integer mathematical programming model to determine a cost minimizing delivery schedule for biorefinery located in Monroe County in East Tennessee. The delivery schedule was influenced by the plant size, bale type, dry matter losses during storage, machinery capacity, land and harvest equipment availabiltiy. For a small scale biorefinery, more productive land which was close to the biorefinery was contracted. As the plant size was enlarged, less productive land which was relatively further away from the biorefinery were selected to meet the plant demand.

Storage was not necessary from November to January when switchgrass was available for harvest and there were no constraints on available harvest equipment. Rectangular bales were preferred in such early months. In February, both rectangular bales and round bales were harvested with the rectangular bales being delivered to the plant and the round bales being put into storage. The round bales are stored without protection if scheduled for early delivery and with tarp and pallet protection if scheduled for later delivery. The mixture of round and rectangular bales resulted in lowered delivered costs than did a round bale only or a round bale only system. Round bales stored on pallets and had a tarp cover provided the lowest dry matter losses in the analysis. The delivered cost in terms of per gallon of ethanol produced was positively related to plant size and dry matter losses during storage. The limited availability of productive soils close to the biorefinery caused costs to rise with increasing plant size.

There are several limitations in this analysis. Pre-processing and processing costs once the feedstock was delivered were not included in this analysis. Given that the biorefiney's profit equals the revenue from selling ethanol minus the cost from producing ethanol, the processing cost is an important factor in determining the cost of ethanol production. Further study on the benefits and costs on pre-processing and processing activities may disclose more information on the feasibility of using switchgrass as a bioenergy crop.

VITA

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