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

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Abstract: Switchgrass for bioenergy production will require substantial storage. This study evaluated costs of alternative baling and on-farm storage systems. Rectangular bales minimize cost if switchgrass is processed immediately after harvest. However, round bales minimize cost if switchgrass is stored under cover for 200 days before transporting to the biorefinery.

Keywords: switchgrass, baling, storage, transport, costs, farm, biorefinery

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Switchgrass is considered a potential leading energy crop for ethanol production (McLaughlin S.B. and L.A.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 (English, Larson and Mooney, 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 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 of different on-farm harvest and storage methods and arrangements. Our research evaluates the cost of alternative farm-level harvest, storage and transportation methods to deliver switchgrass to the biorefinery considering typical farm resources, farm constraints, and weather conditions in East Tennessee.

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 dry ton/acre yield, harvest costs were

$19.06 dry/ton and $14.68 dry/ton for round bale and rectangular bale. However, the storage costs were $3.83 dry/ton and $16.97 dry/ton for round bale and rectangular bale respectively. They found that the difference in costs becomes less significant, when the yield is above 3.64 dry ton/acre and storage losses for round bales stored outside increase above 5%. Sokhansanuj and Turhollow (2002) compared two harvesting systems. Using a round baling system, the costs were $8.89 dry /ton for baling and $6.37 dry/ton for transporting. Using a rectangular baling system, the costs were $8.99 dry/ton for baling and $8.99 dry/ton for transporting. 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 find that the baling cost of switchgrass ranges from $44 to $47 per ton delivered. Although the prior research studied the viability of switchgrass based ethanol production, the production and its costs of switchgrass and the logistics of switchgrass, few of the studies took storage and storage loss into consideration and addressed how the variations such as switchgrass yield, diesel fuel price, and nitrogen fertilizer price under different level of storage loss influenced the delivered costs and the optimal delivering methods. In our study, we integrated these factors to get a better estimate of the delivered costs and optimal logistics. The objective is to assess alternative methods to harvest, store and transport switchgrass to the biorefinery in East Tennessee under the typical on-farm and to provide the optimal pathway.

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 delivered costs in order to achieve high profits from producing switchgrass. For this analysis, it is assumed that currently available hay equipment is used to 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. Thus, production costs including the establishment costs incurred in the first year of production and the recurring annual costs for nutrients, harvest, storage, and transport can be modeled using:

Harvest costs α_h^0 (\$/acre):

$$\alpha_h^{\ 0} = MOW_h(d) + RAKE_h(d) + LOADER_h(d) + BALER_h(d) + TRACTOR_h(d) + LABOR_h \qquad (1)$$

Post-harvest costs α_h (\$/ton):

$$\alpha_h = \frac{EST_0 + NIT(f) + \alpha_h^0}{Y*(1-u_h)} \qquad (2)$$

Post-storage costs γ_{hst} (\$/ton):

$$\gamma_{hst} = \frac{\alpha_h + \gamma^o{}_{hst}}{(1-v_{hst})} \qquad (3)$$

Delivered costs θ_{hst} (\$/ton):

$$\theta_{hst} = \frac{\gamma_{hst} + \theta^o{}_{hst}}{(1-w_{hst})} \qquad (4)$$

where the subscript h is bale type (round or rectangular), the subscript s is storage method, the subscript t is time in storage, *EST* is switchgrass establishment expenses amortized either over the life of a contract to produce switchgrass or over the expected life of the stand (\$/acre); *NIT* is nitrogen fertilization costs; *MOW, RAKE, BALE, STAGE*, and *STORE* are the labor, operating, and ownership costs of mowing, raking, baling, handling, and storing switchgrass (\$/ton), correspondingly. μ is the dry matter loss during harvest. v is the dry matter loss during storage. w

is dry matter loss during transportation. γ^o is the storage cost. θ^o is the transport cost. α is the loss adjusted post harvest cost. γ is the loss adjusted post storage cost. θ is the loss adjusted post transport cost (delivered cost). The variables assumed to be random in equation (1), (2) and (3) 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 nitrogen 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 would occur. Higher switchgrass yields incur more field time per acre to harvest and handle switchgrass, thus greater fuel, labor, and other operating and ownership costs. 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 time, and bale storage method. 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 were: 1) 100 days, 2) 200 days, 3) 300 days, 4) 400 days, and 5) 500 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:

$$DWB_{hst} = \sum_{n=1}^{N} \left(WWB_{hst} \times WA_{hst,n} \times \frac{DSW_{hst}}{WSW_{hst}} \right), \quad (5)$$

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 wet sample weight. Dry weight per bale after harvest (DWB_{hs0}) can be viewed as 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 equation (6):

$$v_{hst} = \frac{DWB_{hs0} - DWB_{hst}}{DWB_{hs0}}. \quad (6)$$

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 in storage before transportation to the biorefinery for processing.

Enterprise Budgeting

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. In accordance with the American Agricultural Economics Association Cost and Return Handbook (AAEA 2000) and American Society of Agricultural Engineers (ASAE) Standards (2000), enterprise budgeting was employed to calculate the costs for each alternative harvest, storage and transport treatment.

(1) Harvest cost per acre α_h^0

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., 20008). The machine time for mowing and raking does not vary with yield. Dry matter loss during harvest is assumed to be zero in this study.

(2) Storage cost per ton γ_{hst}^0

The estimated costs for materials used for the storage of switchgrass bales were obtained through an informal survey by the authors of suppliers. From the informal survey, we obtained the sizes and prices for plastic tarps, gravel, and wooden pallets around Tennessee. Collins et al. (2008) 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 is effective to shed water in the high rainfall humid subtropical climate found in Tennessee and the southeast United States. The price for a tarp that has a dimension of 33 ft by 48 ft averaged $279.09. 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. Gravel can be delivered at an average price of $24.31/ton. We assume that a gravel pad has a 5-inch depth and thus one ton of gravel is assumed to cover 32 sq ft on the ground. Three round bales or 2.5 rectangular bales can be placed an area of 32 sq ft. Three pallets are good for six round bales. Four pallets are good for five rectangular bales. The price of the pallets was $6.50 on average. Since the tarps, gravel and pallets are assumed to have 5 years of life, the costs of tarps, gravel and pallets are amortized by 5 years at zero salvage value. Replacement is 20% for tarps and wooden pallets and is 2% for gravels. The storage cost per ton (γ_{sh}^{0}) is sum of cost of coverage and cost of bottom support.

(3) Transporation cost per ton θ_{hst}^{0}

The cost per hour of the semi-tractor trailer can be obtained as is done for the equipment used in harvesting. The distance from the farm to the plant is assumed to be 50 miles (Tennessee Code). The travel speed of the semi-tractor trailer is assumed to be 50 miles/hour (Brechbill, Tyner, and Ileleji, 2008). As a result, it costs two hours per round trip to the plant. The capacity of the trailer is 36 large round bales or 24 rectangular bales. On average, the trailer carries 13 round bales or 6.5 rectangular bales per hour. The average bale density is 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}) is obtained by dividing the cost per hour by tons per hour the trailer carries. Dry matter loss during transportation is assumed to be 2% for round bales and rectangular bales (Kumar and Sokhansanj, 2006).

Labor time is 1.25 times the corresponding machine time (ASAE Standard, 2000). Wage for each operation is uniformly $8.5/hour (Larson, 2008).

Simulation

Switchgrass yields for Loring soil and Dandridge soil types in East Tennessee were simulated from Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Larson, 2008). Diesel fuel price and nitrogen fertilizer price were simulated from @risk (Larson, 2008). For each soil type, six cumulative density functions of loss adjusted post transport costs (delivered costs) for round bales and four cumulative density functions of delivered costs for rectangular bales were obtained from the simulation 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

Baseline costs

The estimated delivered to the plant costs include those costs occurring in five stages -- establishment, annual fertilization, harvest, storage and transportation. The establishment costs and annual fertilization costs reported by Mooney et al (2008) are incorporated in our analysis. Mooney et al (2008) evaluated the establishment costs to be $51/acre and the annual fertilization costs to be $40/acre. Without considering storage and storage loss, the rectangular bales incur delivered costs of $67.69/ton, which are lower than the $71.99/ton delivered costs of round bales on Loring soil type. On the Dandridge soil type, delivered costs of the rectangular bales are $78.79/ton, which are lower than the $83.08/ton delivered costs of round bales. The delivered costs for switchgrass that are produced on Loring soil is lower than those that produced on the Dandridge soil for a given bale shape. (Table 1)

Storage loss (%) at 200-days

The storage dry matter loss as a percentage of the initial bale dry matter weight for each protection treatment is shown in Table 2. After 200-day of storage, the well covered round switchgrass bales staged on wood pallets generate the lowest storage loss, 8%. The greatest storage loss for the round bales is 21% which results from storing on the wood pallet without tarp. On average, the storage loss after the 200-day storage is 14% for round bales with cover, 19% for round bales without cover. Compared to the round bales, the rectangular bales suffer severe storage loss. The lowest storage loss at 200-day of storage for the rectangular bales is 19% which results from a protection combination of tarp and pallet. The highest storage loss can reach 55% at 200-day of storage for the rectangular bales. On average, the storage loss after 200-day storage is 25% for rectangular bales with cover, and 52% for rectangular bales without cover.

Switchgrass delivered costs after 200-day storage

The delivered costs after 200-day storage are shown in Table 3. After 200-day storage of round switchgrass bales which are produced on a Loring soil type in East Tennessee, the lowest delivered costs are $82.76/ton. Compared to the switchgrass delivered costs after harvest, at least $10.76/ton should be paid for storage loss after 200-day storage for the round bales that are produced on the Loring soil. For the rectangular bales, the combination of tarp and pallet outperforms other storage treatments again. The delivered costs of the rectangular bales protected with tarp and pallet are $2.60/ton more than the corresponding costs of round bales from Loring soil. The cumulative distribution functions show that tarps and pallets are the optimal option for storing the switchgrass regardless the switchgrass bale shape (Figure 1). The probabilities that the delivered costs are less than $75/ton are 63%, 64%, 20% and 14% for round bales on Loring soil type, rectangular bales on Loring soil type, round bales on Dandridge soil type and rectangular bales on Dandridge soil type.

Sensitivity of delivered costs to switchgrass yield

In order to test the sensitivity of the delivered costs to switchgrass yield, the delivered costs for each treatment were plotted under three alternative switchgrass yields of 3 tons/acre, 6 tons/acre and 9 tons/acre. As can be seen, the delivered costs are more responsive to switchgrass yield for the rectangular bales than for the round bales for each storage treatment (Figure 2). When switchgrass yield increases from 3 tons/acre to 6 tons/acre, the delivered costs of "Tarp+Pallet" option decrease by $44.49 tons/acre for rectangular bales and by $39.17 tons/acre for round bales. When switchgrass yield increases from 6 tons/acre to 9 tons/acre, the delivered costs of "Tarp+Pallet" option decrease by $14.83 tons/acre for rectangular bales and by $13.06 tons/acre for round bales.

Conclusion and discussion

The baseline budget shows that the costs to harvest and transport the rectangular bales are lower than the corresponding costs to deliver the round bales to the biorefinery, when storage and storage loss are 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. This infers that farmers need to store their switchgrass for various periods after they harvest switchgrass. The result from this study shows that the storage loss, especially in the rectangular bales, should not be neglected. Furthermore, when farmers store switchgrass for 200 days in East Tennessee, additional compensation of $15.75/ton is required. A compensation of $33.40/ton is needed if rectangular switchgrass bales are stored on farm for 200 days. In practice, we need to adjust the delivered costs for storage loss to provide an adequate storage incentive to farmers. Given this information, to minimize the costs of the feedstock, both types of bales would be preferred. For switchgrass delivered right after harvest, the rectangular bales would be the least expensive. When storage is required, round bales would be the least expensive. 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. For switchgrass that is delivered to the plant after 200-day storage, the round baling system and storage with tarp and pallet are recommended. Further research data on the storage loss of time for each storage treatment will be needed to estimate the appropriate compensation for farmers who are required to store the harvested switchgrass for different periods. This study differs from other research on switchgrass delivered costs 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.

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Table 1. Baseline costs: Switchgrass post-harvest and delivered cost per ton when switchgrass is delivered to the biorefinery immediately after harvest

$/ton	Large Round Bale		Large Rectangular Bale	
	Loring	Dandridge	Loring	Dandridge
Post-harvest costs	52.85	63.72	45.73	56.60
Delivered costs	71.99	83.08	67.69	78.79

* All reported costs are in 2007's dollar

Table 2. Dry matter loss (%) at 200-day of storage

	Large Round Bale	**Large Rectangular Bale**
Tarp + Pallet	8%	19%
Tarp + Gravel	16%	31%
Tarp	19%	------
Pallet	21%	49%
Gravel	17%	55%
None	19%	------

Table 3. Switchgrass post-harvest, post-storage and delivered costs per ton after 200-day of storage

	Large Round Bale		**Large Rectangular Bale**	
	Loring	Dandridge	Loring	Dandridge
	Post-harvest costs (α_h) $/ton			
	52.85	63.72	45.73	56.60
	Post-storage costs (γ_{sht}) $/ton			
Tarp + Pallet	63.41	75.22	62.43	75.85
Tarp + Gravel	72.44	85.38	74.14	89.90
Tarp	69.03	82.45	------	------
Pallet	69.97	83.73	94.87	116.18
Gravel	69.62	82.72	108.83	132.99
None	65.25	78.67	------	------
	Delivered costs (θ_{sht}) $/ton			
Tarp + Pallet	82.76	94.82	85.36	98.43
Tarp + Gravel	91.97	105.18	96.69	112.77
Tarp	88.50	102.19	------	------
Pallet	89.45	103.49	117.84	139.59
Gravel	89.10	102.46	132.09	156.74
None	84.64	98.33	------	------
On average	*87.74*	*101.08*	*108.00*	*126.89*

Figure 1. Cumulative probabilities of delivered costs on Loring and Dandridge soil types

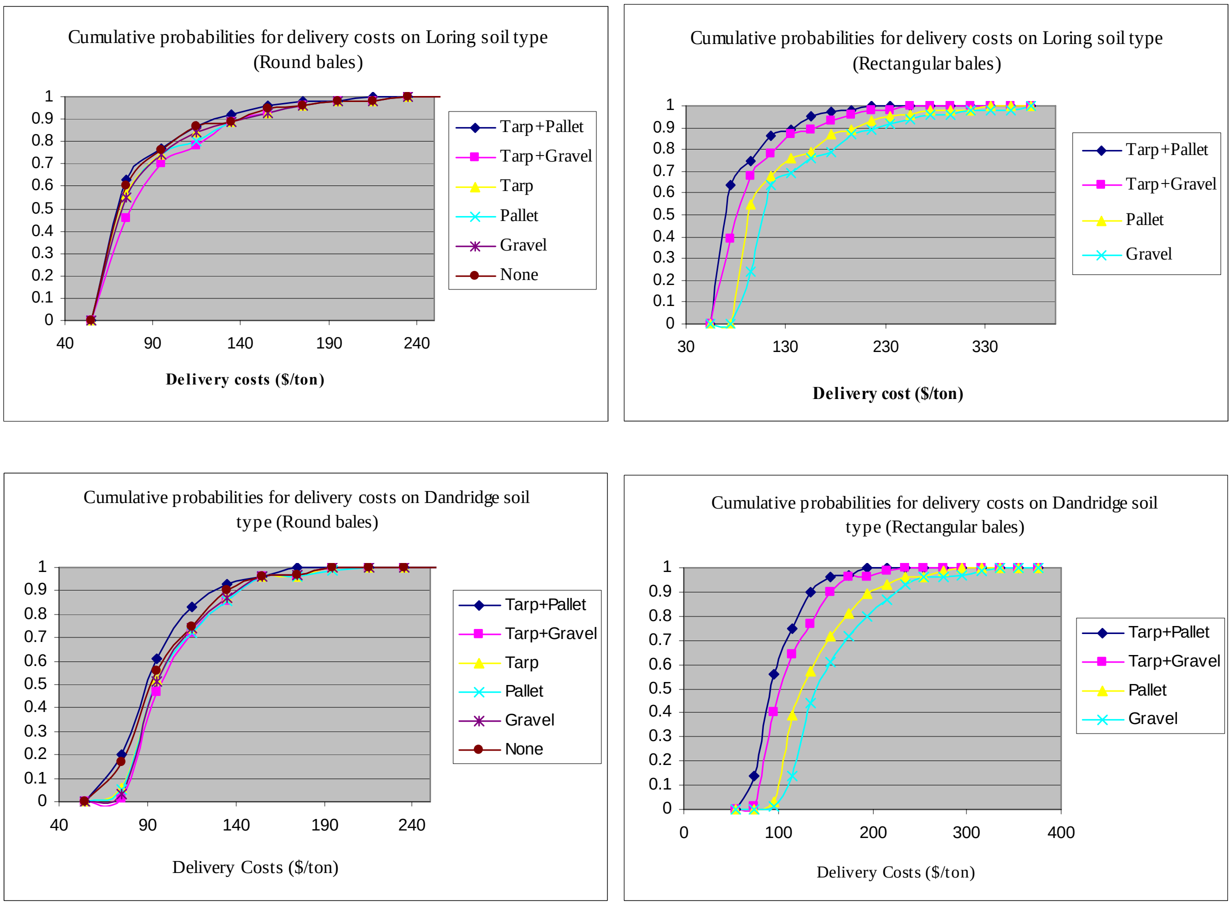

Figure 2. Sensitivity of delivered costs at 200-day of storage to switchgrass yield