Cost evaluation of alternative switchgrass producing, harvesting, storing, and transporting systems and their logistics in the Southeastern USA

James A. Larson, Tun-Hsiang Yu, Burton C. English
and Daniel F. Mooney
Department of Agricultural and Resource Economics,
The University of Tennessee, Knoxville, Tennessee, USA, and
Chenguang Wang
Department of Agricultural Economics, Michigan State University,
East Lansing, Michigan, USA

Abstract

Purpose – The US Department of Energy has a goal to make ethanol from biomass cost competitive with petroleum by 2012. Feedstock procurement is expected to represent a significant portion of the operating costs for a refinery that produces ethanol from biomass such as switchgrass. Thus, cost-effective feedstock logistics will be a key factor for the future development of a capital intensive cellulosic ethanol industry. The purpose of this paper is to analyze the cost of various logistic methods of switchgrass production, harvesting, storing, and transportation.

Design/methodology/approach – This study applied enterprise budgeting and geographical information system (GIS) software to analyze the costs of three logistic methods of acquiring switchgrass feedstock for a 25 million gallon per year refinery. Procurement methods included traditional large round and rectangular bale harvest and storage systems and satellite preprocessing facilities using field-chopped material. The analysis evaluated tradeoffs in operating costs, dry matter losses during storage, and investment requirements among the three systems.

Findings – Results suggest that the preprocessing system outperformed the conventional bale harvest methods in the delivered costs of switchgrass.

Practical implications – The cost savings in harvest, transportation, and dry matter losses for the preprocessing system offset their extensive capital costs and generated cost advantages over the conventional methods.

Social implications – The traditional round bale system has a higher overall investment cost, may not be the most cost-effective way to procure switchgrass feedstock for a refinery, and may limit farmer participation in the feedstock value chain.

Originality/value – GIS methods combined with enterprise budgeting can be useful tools for evaluating investment in feedstock supply chain infrastructure.

Keywords Geographic Information Systems, United States of America, Plants, Fuels, Agriculture, Value chain

Paper type Research paper

Introduction

The Energy Independence and Security Act of 2007 mandates a minimum of 36 billion gallons of renewable fuel production annually in the USA by 2022 (US Congress, 2007).

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To meet the aforementioned goal, lignocellulosic biomass (LCB) from dedicated energy crops, agricultural residues, forest resources, and other by-products will need to be produced on a cost competitive basis with fossil fuel sources (De La Torre *et al.*, 2007). However, substantial technical barriers related to the production, harvest, storage, and logistics of LCB feedstock have yet to be overcome. Feedstock procurement is estimated to represent half of the potential operating costs for a refinery that produces ethanol from LCB feedstock (Forest2Market, 2009).

As part of the national effort to overcome these barriers, the US Department of Energy (DOE) has a goal for its research and development efforts to make ethanol from LCB cost competitive with petroleum by 2012 (US DOE, 2008). The development of an LCB feedstock supply chain will need to be regionally appropriate and one that can use off-the-shelf or near off-the-shelf technologies to meet the 2012 cost goal. For example, switchgrass can be harvested using conventional hay equipment that many farmers already have at their disposal (Jensen *et al.*, 2007). In addition, the LCB feedstock supply chain needs to be flexible enough to incorporate new technologies as they become available, meet the feedstock quality and cost needs of biorefineries, and provide sufficient profits to feedstock suppliers to induce production.

Switchgrass, a warm-season perennial grass native to the USA, is widely recognized as a leading crop for dedicated energy production (McLaughlin and Kszos, 2005). The projected time for the harvest of switchgrass is once in the fall or winter 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 harvestable LCB for conversion to ethanol. Thus, a single, late-season harvest may be a key factor in making switchgrass production a sustainable low-input system. Given that a refinery will need a supply of feedstock throughout the year, storage of switchgrass before processing will likely be an important activity in the feedstock supply chain. Switchgrass is bulky relative to the energy contained, so it is comparatively expensive to harvest, store, and transport and thus these logistical processes are essential determinants of the cost of ethanol from switchgrass (Carolan *et al.*, 2007). In addition, dry matter losses from precipitation and weathering during storage may substantially diminish the quantity and quality of switchgrass after harvest and increase the costs of feedstock delivered to the biorefinery (Cundiff and Grisso, 2008). This may be particularly true in the southeastern USA where precipitation tends to be higher year-round relative to other regions.

Researchers have evaluated different aspects of the feasibility and costs of harvesting, storing, and transporting LCB feedstock using currently available harvest technologies but have not evaluated the impact of dry matter losses for different harvest methods, storage methods, and storage periods on the costs of producing switchgrass (e.g. Thorsell *et al.*, 2004; Bransby *et al.*, 2005; Mapemba *et al.*, 2007; Kumar and Sokhansanj, 2007; Perrin *et al.*, 2008). Two currently available harvest technologies, large round balers and large rectangular balers, may have certain advantages and disadvantages in a potential LCB feedstock supply chain. A large round bale is designed to shed water and may have an advantage over a large rectangular bale with respect to dry matter losses when stored outdoors (Cundiff and Grisso, 2008). However, a large rectangular bale system, which has a larger throughput capacity than a large round bale system, may have harvest, handling, and storage economies of size advantages over large round bales (Thorsell *et al.*, 2004; English *et al.*, 2008). Notwithstanding the potential cost advantages of rectangular bale harvest, dry matter losses during storage may be greater than for large round bales. Larson *et al.* (2010), using data from a switchgrass storage experiment, estimated storage dry matter loss for a rectangular bale of switchgrass that was covered with a tarp and stored outdoors was 30 percent after 360 days in storage under Tennessee conditions. By comparison, the estimated storage dry matter losses after 360 days in storage for round bales of switchgrass wrapped with twine and stored outside with and without a tarp cover were 9 and 13 percent, respectively. The storage dry matter loss estimated in the study for uncovered switchgrass round bales is similar to the losses reported in a limited set of other studies addressing this issue (Johnson *et al.*, 1991; Wiselogel *et al.*, 1996; Sanderson *et al.*, 1997).

Researchers have proposed the development of regional LCB preprocessing facilities that would be a part of the supply chain feeding into a biorefinery as a way to address storage dry matter losses, high transportation costs, and other potential logistical issues with using traditional hay harvest and storage technologies (Carolan *et al.*, 2007). The preprocessing facility may conduct processing activities such as cleaning, separating and sorting, chopping, grinding, mixing/blending, moisture control, densification, and packaging of feedstock before it is placed into storage or transported to the biorefinery. The key question with this approach is whether the potential saving in storage and transportation costs more than offset the investment in preprocessing technologies. Thus, the objective of this study is to analyze the cost of various logistic methods of switchgrass, ranging from conventional hay methods to the potentially more capital intensive preprocessing option, using enterprise budgeting and geographical information system (GIS) analysis. This study evaluates tradeoffs in dry matter losses during storage, investment, and operating costs of equipment and facility, and the potential savings in transportation costs among three different methods.

Conceptual framework

For this analysis, it is assumed that currently available equipment will be used to establish, maintain, harvest, stage, and store switchgrass before it is transported to the ethanol plant. The objective of the biorefinery is to minimize the cost of switchgrass LCB feedstock delivered to the plant. Costs of switchgrass production ($/dry ton [dt]) include opportunity cost on land; establishment costs incurred in the first year of production; and recurring annual costs for nutrients, pest control, harvest, preprocessing, storage, and transportation to the biorefinery.

Following Wang (2009), these costs can be modeled using:

$$\text{Pre-harvest costs (\$/acre):} \quad \alpha = LAND + EST + AMC, \tag{1}$$

$$\text{Harvest costs (\$/acre):} \quad \beta_h = MOW_h + RAKE_h + HARVEST_h(y) + HANDLE_h(y), \tag{2}$$

where *LAND* is the land rental rate ($/acre); *EST* is the switchgrass establishment cost amortized over the life of a contract to produce switchgrass ($/acre); *AMC* is the annual maintenance cost which includes costs of fertilization and pest control ($/acre); y is the switchgrass yield (dt/acre); h is the harvest method; and *MOW*, *RAKE*, *HARVEST*, and *HANDLE* are the labor, operating, and ownership costs of mowing, raking, harvesting, and handling (potentially including preprocessing) of switchgrass before being placed into storage ($/acre), respectively. Based on previous experience of the University of Tennessee Biofuels Initiative, mowing and raking costs were assumed constant on a per-acre basis regardless of yield levels (Mooney *et al.*, 2009). By contrast, harvest and handling costs were modeled as a function of yield and varied depending on throughput capacity, as shown in Table I.

Plant gates costs were then determined using Equations (3)-(5) to adjust for dry matter losses during harvest, storage, and transportation:

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

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

and

$$\text{Plant gate cost (\$/dt):} \quad \theta_{hst}^p = \frac{\gamma_{hst}^p + \theta_{hst}}{(1-\omega_{hst})}, \tag{5}$$

where s is storage method, t is time in storage (days) before being processed into ethanol, μ is the dry matter loss during harvest and handling before storage, ν is the dry matter loss during storage, ω is dry matter loss during transportation, θ is transportation cost to the biorefinery (\$/dt), β^p is loss-adjusted post harvest cost (\$/dt), γ^p is loss-adjusted post storage cost (\$/dt), and θ^p is loss-adjusted post transport cost to the biorefinery (\$/dt).

Data and methods

Scenarios

An ethanol biorefinery with an annual capacity of 25 million gallon per year was assumed for the analysis. Annual capacity was based on author discussions with executives of Genera Energy LLC and DuPont Danisco Cellolusic Ethanol LLC about the potential size

Item	Month November	December	January	February	Total
Available harvest time (days/hours)[a]					
Days	14	14	13	12	53
Total hours	86	82	78	79	325
Land area harvested (acres/harvester)[b]					
Round baler	79	75	72	72	298
Rectangular baler	173	164	157	157	651
Chopper	288	273	261	262	1,084
Biomass harvested (dry tons/harvester)[b]					
Round baler	475	451	431	432	1,789
Rectangular baler	1,036	983	940	943	3,903
Chopper	1,727	1,639	1,567	1,572	6,505

Notes: [a]Estimated harvest days assuming that 70 percent of the days per month when precipitation was less than 0.01 in. were available for harvest operations (Knoxville, Tennessee, precipitation data). Available harvest hours assume an average 60 percent of daylight hours (Knoxville, TN, daylight hours) of harvest time per available harvest day; [b]assumes an average switchgrass yield of 6 dt/acre and a throughput of 5.5 dt/h for the large round baler, 12 dt/h for the large rectangular baler, and 20 dt/h for a self-propelled chopper

Sources: Dry days, NOAA, US Department of Commerce, Daylight hours, US Naval Observatory; Hanna, 2002; Mooney *et al.*, 2009

Table I. Estimated available harvest time, land area harvested, and biomass harvested for alternative harvest methods for switchgrass in Tennessee of a first-generation commercial cellulosic ethanol biorefinery in East Tennessee (Jackson, 2010). Using the Biomass Feedstock Composition and Property Database (US DOE, 2010a) and the Theoretical Ethanol Yield Calculator (US DOE, 2010b), the theoretical ethanol yield is estimated to range from 96.6 to 110.6 gallons/dt with an average theoretical ethanol yield of 105.3 gallons/dt based on 21 whole plant switchgrass samples. Ethanol yields are limited to 50 to 80 percent of the theoretical potential, partly because lignin cannot be broken down by this process (Mclaughlin *et al.*, 1999). Thus, a conversion rate estimated by Wang *et al.* (1999) of 76 gallons/dt was used to estimate LCB needs for the plant. At this rate of conversion, a biorefinery of this size and operating 360 days per year would require about 329,000 dt of LCB.

Given that switchgrass would be harvested only once after senescence to minimize the harvest of plant nutrients and maximize the yield of LCB, the biorefinery would need to use stored feedstock when harvest was not taking place. The assumed harvest period for switchgrass is between November 1 and March 1. Based on historical weather for Knoxville, Tennessee, a total of 53 days would be suitable for harvest operations during the four-month period (Table I). This translates into 325 h available for harvest or about 6 h per suitable harvest day.

The logistic costs of delivering switchgrass to the plant gate were evaluated for three potential harvest and storage methods:

(1) harvest using a large round baler and storing the feedstock on-farm;

(2) harvest using a large rectangular baler and storing the feedstock on-farm; and

(3) harvest using a forage chopper and hauling to a preprocessing facility for densification and packaging before being placed in on-site storage at the facility.

The round bale scenario represents currently available harvest technology on many southeastern farms and is consistent with individual farmers handling harvest and storage logistics (Jensen *et al.*, 2007). The rectangular bale and preprocessing scenarios potentially provide economy of size advantages (Table I) and therefore may be advantageous when feedstock procurement is handled by someone other than individual farmers, such as an agricultural cooperative or the feedstock purchaser (Thorsell *et al.*, 2004; Carolan *et al.*, 2007). Nevertheless, potential differences among management structures and the associated costs and risks for the three scenarios were not explicitly modeled in this study.

While circles are typically used to represent feedstock area in bioenergy analysis, a more typical road system can be represented by an east-west, north-south grid system in most of the USA. Thus, the loci of points that are equidistant from a processing plant form a diamond-shaped area (English *et al.*, 1981). In this study, the assumed feedstock draw area for the biorefinery is diamond shaped with a maximum shipping distance of 50 miles (Epplin, 1996). For the round and rectangular bale systems, the average distance from farms to biorefinery was 35.5 miles. It is further assumed that one-third of all traditionally harvested bales are delivered directly to the biorefinery following harvest, with the remaining bales stored on-farm.

The preprocessing system required that the diamond feedstock draw area be split into four shipping zones. LCB harvested using a forage chopper in the center zone was assumed to be delivered directly to the biorefinery during the harvest season. The remaining area was split into three equal-size zones where a preprocessing facility was located (Figure 1). Using Arc GIS, the centroid points can be located for each region. The

Zone	Travel distance To Biorefinery	Travel distance Within Zone
1. Biorefinery	NA	15.6
2. North	30.0	17.7
3. Southeast	26.0	18.8
4. West	30.0	16.0

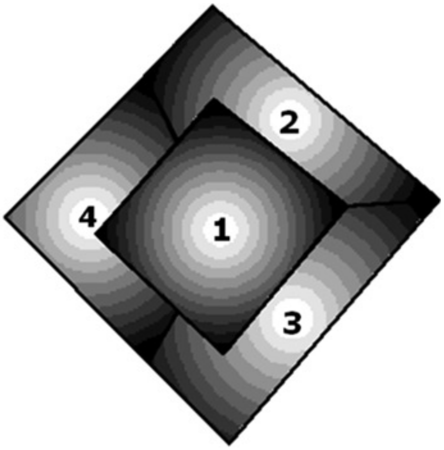

Figure 1.
Biorefinery and satellite preprocessing facilities feedstock draw areas

average travel distance in the rectangle representing the center zone that has the biorefinery was calculated using Pythagoras' theorem. The centroid points of the other three zones define the locations of the preprocessing facilities. The average distances within each zone and from the preprocessing facility to the biorefinery were estimated using Arc GIS (Figure 1). The average distance from the preprocessing facilities in three zones to biorefinery was between 26 and 30 miles. The average travel distance from farms to the preprocessing facility in each preprocessing zone was less than 20 miles.

The preprocessing scenario analyzed here is based on an industrial compactor and bale wrapper developed originally in Europe for garbage and is marketed in the USA by TLA BaleTech LLC. For switchgrass, the technology creates a 2 dt condensed bale about the same dimensions as a conventional large round bale (Falconi, 2010). The condensed bale is enclosed in a mesh net that is two to three times stronger than agricultural bale netting and multiple layers of a proprietary high tensile strength film that contracts around the bale to force out any air and seal the bale. To accommodate the preprocessing operation, we assume that each preprocessing facility consists of a building to house the industrial baler, covered storage for a two-day supply of chopped switchgrass from producer fields, and sufficient land for on-site storage of preprocessed bales.

Table II summarizes the operation sequences of supplying switchgrass to the biorefinery in each logistic system. For the large round and rectangular bale systems, there were seven steps involved, including mowing, raking, baling, staging, storing, loading, and transporting to the plant gate. In the preprocessed bale system, four additional steps were required. Following harvest with a self-propelled forage chopper, the LCB was assumed to be transported to a preprocessing facility, dumped into a holding area, front-end loaded onto a conveyor, and condensed into a 2 ton bale wrapped in mesh and plastic to provide anaerobic storage.

Storage dry matter losses

Values for dry matter loss during storage differed among the scenarios considered. Storage dry matter loss data for the large round and rectangular bales were from a switchgrass harvest and storage study at the Milan Research and Education Center in Milan, Tennessee (English *et al.*, 2008). The treatments in the study were bale harvest method, bale storage method, and bale storage time. Round bales (5 ft × 4 ft) and

Table II.
Operations sequence by harvest method

Operation	Round bale	Rectangular bale	Compactor/ baler/wrapper
Mow	1	1	1
Rake	2	2	2
Bale	3	3	–
Chop	–	–	3
Haul by truck to preprocessing facility	–	–	4
Dump in holding area	–	–	5
Front-end load into conveyer	–	–	6
Compact/bale/wrap	–	–	7
Front-end load to storage	4	4	8
Store	5	5	9
Front-end load to truck	6	6	10
Haul by semi-truck to biorefinery	7	7	11

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 tarp on one of three storage surfaces are:

(1) well-drained ground;
(2) a gravel surface; and
(3) a wooden pallet.

For the large round bales, the six storage treatments were:

(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) covered on wooden pallets.

For the rectangular bales, the four storage treatments were:

(1) uncovered on gravel;
(2) uncovered on wooden pallets;
(3) covered on gravel; and
(4) covered on wooden pallets.

The five target bale storage times in the experiment were:

(1) 100 days;
(2) 200 days;
(3) 300 days;
(4) 400 days; and
(5) 500 days.

Each treatment was replicated three times. The detailed procedure for the sampling of the switchgrass bales and the estimation of storage dry matter losses for each treatment using the wet and dry weights for each sample is presented by English *et al.* (2008) and Wang (2009). Storage dry matter loss equations estimated by Larson *et al.* (2010) using data from the experiment were used to model dry matter losses during storage in the analysis. The Mitscherlich-Baule functional form imposed diminishing dry matter losses as a function of time and an asymptotic dry matter loss plateau. Thus, the functional form is consistent with the notion that the losses will stop at some point when no organic matter is left to oxidize (Hoglund, 1965; Savoie *et al.*, 2006). Given that dry matter losses for each bale type and storage method were assumed to be zero when bales were placed in storage, the dry matter loss models were estimated without an intercept.

For the preprocessing scenario, dry matter losses for forage chopper harvest and transport to the preprocessing facility in a truck covered with a tarp were assumed to be the same as the dry matter losses for the two traditional bale systems during the harvest and staging of switchgrass before being placed in storage. Dry matter losses for switchgrass stored in preprocessed bales were not directly available. However, data from a study of the decomposition of garbage (kitchen waste, grass clippings, paper, plastics, and other inert materials) that was condensed and stored using the same technology indicated no methane formation and an absence of anaerobic biodegradation (i.e. dry matter loss) after eight months of outside storage (Robles-Martinez and Gourden, 2000). Thus, the dry matter losses were assumed to be negligible once the preprocessed bales were protected by the mesh and film wrapping. While not modeled in the present analysis, the preprocessed bale option also has the potential to facilitate pretreatment of bales to enhance the quality of LCB in storage and processing (Carolan *et al.*, 2007).

Enterprise budgeting

The yield assumptions and budgets for the equipment, materials, and labor used for the establishment, annual maintenance, harvest, storage, and transportation of switchgrass were from budgets produced by The University of Tennessee Department of Agricultural and Resource Economics (Gerloff, 2008; Mooney *et al.*, 2009; English *et al.*, 2008; Wang, 2009). An average harvested yield going into storage of 6 dt/acre was used to calculate the cost per ton of producing switchgrass. The costs estimated for each budget were made in accordance with the *American Agricultural Economics Association Cost and Return Handbook* (AAEA, 2000) and American Society of Agricultural Engineers (ASAE) Standards (ASAE, 2006). For the purpose of calculating costs, all land, buildings, equipment, and materials were assumed to only be used for switchgrass production. Items having useful lives of more than one year were amortized using the capital recovery method and a real interest rate of 3 percent (AAEA, 2000). The cost of diesel fuel for all equipment operations was $2.35/gallon (McKinley and Gerloff, 2010). Labor time was assumed to be 1.25 times the corresponding machine time (ASAE, 2006) and the wage for each operation was assumed to be $9.50/h (McKinley and Gerloff, 2010). The opportunity cost on land used for switchgrass production was $22/acre, the pasture land rental rate reported for 2008 by the Agricultural Statistics Database of the National Agricultural Statistics Service (USDA, 2009).

Pre-harvest cost. Establishment costs were amortized over an assumed contract period of five years and treated as an annualized cost. Annual maintenance costs included nitrogen fertilization and pest control primarily for weeds. Nitrogen fertilization was assumed at the Extension-recommended level of 60 lb nitrogen/acre at

$0.65/lb (Gerloff, 2008). University of Tennessee extension only recommends that phosphorous and potassium be applied on deficient soils and thus it was assumed that none was used in calculating costs.

Harvest cost. The equipment assumed for the round bale harvest included a 5 ft × 4 ft large round baler, a mower, a rake, and a loader and a tractor. The rectangular bale harvest used a 4 ft × 8 ft rectangular baler in place of the round baler. After harvest, switchgrass bales were assumed to be transported by a tractor with a loader to the field edge for storage before being shipped to the biorefinery. 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 balers were assumed to be linearly related to yield based on a throughput capacity of 5.5 and 12 dt/h, respectively, for the large round and rectangular balers (English *et al.*, 2008; Mooney *et al.*, 2009). The machine times for mowing and raking were assumed not to vary with yield (Mooney *et al.*, 2009). Dry matter losses were assumed to be the same for both bale harvest methods and thus not accounted for in the analysis.

The harvest equipment assumed for the preprocessing facility system included a self-propelled forage chopper, a tandem-axle truck, a mower, a rake, and a tractor. After harvest, chopped LCB was assumed to be transported by a tandem-axle truck to the storage area in the preprocessing facility. The total harvest cost per acre is the sum of the per acre costs of mowing, raking, chopping, and transporting to the holding area at the preprocessing site. Machine time of the chopper was based on an assumption of a throughput capacity of 20 dt/h (Hanna, 2002).

Preprocessing cost. The estimated costs of a preprocessing facility included land, roads, utility infrastructure, and taxes in an east Tennessee industrial park located in a typical small east Tennessee city (Table III). The industrial compactor with supporting conveyor equipment is estimated to have an initial purchase price of $1.4 million, a useful life of 36,000 h, and a throughput capacity of 60 dt/h (Table III). Thus, the machine over a four-month season (88 days) would be able to process 84,480 dt (16 h/day for 22 days/month). At assumed yield levels, the preprocessing facility would require an average of 266 acres of switchgrass harvested per suitable field day. In addition, costs of a building for the machine and sufficient covered storage for two days of chopped material were estimated to be $596,942 (Table III). The cost of materials for each preprocessed bale (film and net wrap) that was processed through the facility was assumed to be $9.60/2 dt bale (Falconi, 2010).

Storage cost. The estimated costs for materials used for the storage of the large round and large rectangular switchgrass bales were obtained from an informal survey of suppliers located in Tennessee. The costs included materials for plastic tarps, gravel, wooden pallets, and equipment and labor required to create the storage site and bale stack (Wang, 2009). Collins *et al.* (2008) 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 the southeastern USA. Thus, the large round bales were assumed to be stored in a stack using this configuration. The bales produced at the preprocessing facility were also assumed to be stored in 3-2-1 pyramids on site until transport to the biorefinery. The large rectangular bales were assumed to be stored in a 2-2-1 configuration.

Transportation cost. The cost of the semi-tractor trailer was obtained using the same budget procedures as used for harvest equipment. For the round and rectangular bale

Table III. Selected equipment budgets for alternate switchgrass harvest and preprocessing systems

Item	Unit	Preprocessing scenario			Baler scenarios	
		Chopper	Preprocess baler	Buildings	Round baler	Rectangular baler
Cost calculation parameters						
Purchase price (PP)	$	266,000	1,400,000	596,942	23,000	87,700
Useful life[a,b]	h	4,000	36,000	36,000	1,500	3,000
Annual use[c]	h/year	325	1,218	1,218	325	325
Repair factor[a]	% of PP	48	100	59	90	72
Salvage value[a]	% of PP	25	10	0	40	30
Throughput performance	dt/h	20	60	–	5.5	12
Electricity use (in operation)	kW/h	–	2,010	–	–	–
Electricity use (stand by)	kW/h	–	60	–	–	–
Land costs[d]	$	–	–	300,000	–	–
Ownership costs						
Depreciation and interest[a,e]	$/h	64.29	1.92	0.85	8.76	24.92
Taxes, insurance, and housing[a]	$/h	16.37	14.73	6.13	3.29	5.40
Annualized land cost	$/h	–	–	19.93	–	–
Tractor ownership costs	$/h	–	–	–	28.29	28.29
Operating costs						
Repairs and maintenance[a]	$/h	37.55	38.89	9.80	13.80	24.85
Equipment operator[a,f]	$/h	12.19	12.19	12.19	12.19	12.19
Fuel and oil[a,g]	$/h	53.27	–	–	–	–
Electricity[i,h]	$/h	–	11.04	–	–	–
Property taxes	$/h	–	–	7.25	–	–
Tractor operating costs	$/h	–	–	–	39.58	39.58
Total cost	$/h	183.67	78.77	56.15	105.91	135.23

Notes: [a]Determined using ASAE (2006) and AAEA (2000) standards; except for preprocess baler which was assumed to have a repair factor of 100 percent and a salvage value of 10 percent of purchase cost; [b]useful life and cost of preprocess baler from personal communication with Jose Falconi, Chief Development Officer, TLA BaleTech LLC, January 2010; useful life of building facilities assumed identical to the preprocess baler; [c]annual use of preprocess baler determined assuming baler operates 16 h/day for 88 days during the November 1 to March 1 harvest window; [d]based on a 15-acre land requirement for the preprocessing facility valued at $20,000/acre (informal survey by the authors); [e]calculated using the capital recovery method with a 3 percent discount rate (AAEA, 2000); [f]based on a hired labor cost of $9.75/h and a labor requirement of 1.25 h per machine hour (McKinley and Gerloff, 2010); [g]based on a fuel price of $2.35/gallon and a 450 hp engine (McKinley and Gerloff, 2010); [h]preprocess baler is used 16 h per day during the November 1-March 1 harvest window; [i]based on an electricity price of $0.08/kWh (US DOE, 2010c) and energy consumption parameters provided by TLA BaleTech LLC (2009)

systems, the average distance traveled from the farm to the biorefinery was assumed to be 37.5 miles. For the preprocessing facility system, the average distance between farms and the preprocessing facility within each zone was 17.0 miles and the average distance from three preprocessing zones to the center zone was 28.7 miles (Figure 1). The average travel speed of the semi-tractor trailer was assumed to be 50 miles/h (Brechbill *et al.*, 2008). For the 50 miles/h scenario, the time per round trip to the plant was assumed to be 1.42 h for the large round and rectangular bale systems and 1.15 h for the preprocessing facility system. The capacity of the trailer was assumed to be 36 large round bales, 24 rectangular bales, or 13 preprocessed bales. On average, the trailer carried 13 tons of round bales per trip, 16 tons of rectangular bales per trip, or 26 tons of preprocessed bales per trip. Thus, one could haul twice as much switchgrass with preprocessed round bales as compared to traditional round bales. Assuming that a semi-truck can operate 10 h per day, the large round bales, large rectangular bales, and preprocessed bales needed ten, eight, and four trucks per day, respectively. Finally, the average cost per ton of transportation 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 (Kumar and Sokhansanj, 2007).

Results and discussion

Operation cost of switchgrass production

Table IV summarizes estimated total costs of switchgrass production by harvest and storage methods following the operations sequence in Table II. The logistic costs presented in Table IV do not take into account the dry matter losses in storage, so it can be viewed as the cost of the bales with 0 days of storage. The total cost of producing switchgrass using rectangular bales was estimated to be \$78.27/dt if it was delivered to the biorefinery for processing immediately after harvest. Because of the costs of baling

Table IV.
Summary of costs by operation under each harvest method without storage dry matter loss (per dt)

Operation	Round bale	Rectangular bale	Preprocess bale
Pre-harvest	21.33	21.33	21.33
Mow and rake	9.03	9.03	9.03
Bale	19.52	11.27	–
Chop	–	–	9.18
Haul by truck to preprocessing facility	–	–	7.16
Dump in holding area	–	–	1.92
Front-end load into conveyer	–	–	1.92
Compact/Bale/Wrap	–	–	6.89
Front-end load to storage[a]	14.88	14.88	1.92
Store			
Right after harvest	0.00	0.00	0.00
Tarp + pallet	7.75	5.64	–
Tarp + gravel	17.78	10.75	–
Tarp	4.84	–	–
Gravel	13.92	–	–
Pallet	4.33	–	–
Load to semi-truck and deliver to biorefinery	11.95	9.84	5.10
Total			
Round bale: no protection	78.27	–	–
Round bale: tarp + pallet	86.18	–	–
Round bale: tarp + gravel	96.41	–	–
Round bale: tarp	83.21	–	–
Round bale: gravel	92.47	–	–
Round bale: pallet	82.69	–	–
Rectangular bale: no protection	–	67.70	–
Rectangular bale: tarp + pallet	–	73.45	–
Rectangular bale: tarp + gravel	–	78.66	–
Preprocessed bale	–	–	65.76

Notes: [a]For the traditional bale systems, biomass was assumed to be move at a rate of 8 dt/h from the field to storage (Mooney *et al.*, 2009). For the preprocessed bales, biomass was assumed to be moved at a rate 60 dt/h from the baler to storage by two four-wheel-drive tractors with loaders and transportation, the cost of round bales without any storage protection was about $10/dt higher than that of rectangular bales. With additional protection for storage, such as tarp coverage and pallet base, or tarp coverage and gravel base, the total cost of producing switchgrass using round bales can be nearly 23 percent higher than the rectangular bales when the dry matter losses during storage were not considered.

Despite the additional cost of preprocessing facility and operations for the preprocessed bale option, the total cost was less than the rectangular bale option. The cost advantage in the preprocessing facility system primarily came from the lower harvest, handing, and transportation costs. The results suggest that the harvesting, handling, and transportation cost advantages of preprocessed bales are the crucial factors in determining the least cost logistics for bulky LCB.

Cost of production adjusted for storage losses

Consistent with Thorsell *et al.* (2004), the estimated cost/dt of switchgrass was less with the rectangular bale harvest system than with the round bale system if storage dry matter losses were not considered. With conventional hay technology, the least cost method of producing switchgrass processed into ethanol immediately after harvest was the rectangular bale system. In addition, more tonnage was harvested in a limited harvest window with the rectangular baler than with the round baler. Assuming a four-month harvest season with a total of 53 suitable field days (325 field hours) for harvest, one rectangular baler could harvest 651 acres (3,903 dt) of switchgrass compared with 298 acres (1,789 dt) for the round baler.

As indicated previously, storage dry matter losses increased at a decreasing rate with time and cumulative precipitation (Larson *et al.*, 2010). As a result, losses during storage increased the cost of feedstock with longer storage times (Table V). Choice of storage method also had a substantial impact on the cost of switchgrass. Results indicate that the gravel storage pad with or without a tarp cover was not feasible because of the high initial cost to install the pad (Table V). Thus, the least cost method of producing

	Round bale						Rectangular bale		
Days	None	Tarp + pallet	Tarp + gravel	Tarp	Pallet	Gravel	None	Tarp + pallet	Tarp + gravel
0	78.27	NA	NA	NA	NA	NA	67.70	NA	NA
30	80.22	86.90	97.23	83.90	84.77	94.83	NA	78.08	83.67
60	81.83	87.59	98.02	84.57	86.50	96.80	NA	82.23	88.16
90	83.17	88.27	98.79	85.21	87.92	98.42	NA	85.86	92.09
120	84.26	88.92	99.53	85.84	89.08	99.75	NA	88.99	95.48
150	85.15	89.56	100.25	86.45	90.03	100.82	NA	91.63	98.34
180	85.86	90.17	100.95	87.04	90.79	101.69	NA	93.84	100.73
210	86.44	90.77	101.63	87.62	91.41	102.39	NA	95.66	102.70
240	86.90	91.34	102.29	88.17	91.90	102.95	NA	97.15	104.31
270	87.27	91.90	102.92	88.70	92.29	103.40	NA	98.36	105.62
300	87.56	92.44	103.54	89.22	92.60	103.76	NA	99.34	106.67
330	87.79	92.96	104.13	89.72	92.85	104.04	NA	100.12	107.52
360	87.98	93.46	104.70	90.20	93.05	104.26	NA	100.74	108.19
Average[a]	83.02	88.80	99.39	85.73	87.76	98.24	NA	86.22	92.48

Notes: [a]Average for preprocessed bale: 59.41; average cost weighted by the volume delivered to biorefinery each month over a year

Table V. Delivered costs of switchgrass to ethanol refinery by harvest method ($/dt) switchgrass under Tennessee storage conditions was to harvest the switchgrass using a round baler and storing the bales without any protection. Protecting the bales during storage with a tarp and a pallet or gravel surface increased the delivered cost relative to the no-protection scenario. The round bales modeled in this study assumed twine-wrapped bales. Round bales wrapped with mesh appear to have a more uniform shape that may facilitate handling and storage and may have lower storage losses (Johnson *et al.*, 1991). Thus, the potential cost advantage of uncovered round bales relative to other bale type and storage methods may be greater with mesh-wrapped bales.

Assuming that one-third of switchgrass production was delivered to biorefinery immediately after harvest in the harvest season and the remaining two-thirds of switchgrass production were uniformly delivered to the plant from March through October, the round bale technology without any protection was the most cost-efficient approach ($83.02/dt), followed by the round bale with tarp cover ($85.73/dt) and the rectangular bale with tarp cover and pallet base ($86.22/dt). However, with the preprocessing system, the weighted-average delivered cost of switchgrass was only $59.41/dt, about 40 percent lower than the least cost conventional hay system. Results indicate that the advantage of lower harvest, handling, and transportation costs and negligible dry matter losses for the preprocessed bales over the large round or rectangular bales was even apparent in the longer term. Finally, as a sensitivity analysis, the average road speed was reduced to 35 miles/h to evaluate the impact of travel time on plant gate costs. Reducing the travel speed for LCB transported to the biorefinery for processing from 50 to 35 miles/h increased plant gate costs by about 5 percent for each logistical option evaluated in this analysis. In addition, reducing the useful life of the industrial baler (Table III) by half to account for possible obsolescence of the technology increased plant gate costs by less than 2 percent.

Investment cost of production, harvest, and preprocessing equipment

For all three scenarios, the equipment, buildings, and land used for harvest and storage logistics could potentially be used for other activities. However, the total capital investment cost estimates reported in Table VI assumed dedicated use for switchgrass

Table VI.
Total capital investment cost by harvest method ($)

Operation	Round bale	Rectangular bale	Compactor/baler/wrapper
Harvest equipment			
Mower	273,000	273,000	273,000
Rake	81,000	81,000	81,000
Baler	4,232,000	7,454,500	–
Forage chopper	–	–	3,724,000
Subtotal	4,586,000	7,808,500	4,078,000
Preprocessing facility			
Front-end loader	–	–	67,500
Compactor-baler-wrapper	–	–	4,200,000
Building	–	–	1,790,827
Land	–	–	72,823
Subtotal	–	–	6,131,150
Vehicle			
Tractor	26,169,000	12,012,000	6,006,000
Tandem axle truck	–	–	2,940,000
Semi-truck and trailer	1,200,000	960,000	480,000
Subtotal	27,369,000	12,972,000	9,426,000
Total	31,955,000	20,780,500	19,635,150

production, which can be viewed as an upper bound on the capital costs for all equipment, buildings, and land.

In the category of harvest equipment, rectangular bale technology required the largest capital investment, primarily for the 4 ft × 8 ft rectangular baler. It is estimated that 85 balers were required for the rectangular bale system, while 184 round balers were needed to meet the demand from biorefinery. For each of the three preprocessing facilities, a total of 14 self-propelled choppers were required to provide LCB for the preprocessed bale option. For each of the three harvest systems, 42 mowers and 27 rakes were required for harvest.

Based on the throughput of the round baler and rectangular baler, it is estimated that 183 and 84 tractors were needed for the round bale system and rectangular bale option, respectively. This baler machinery requirement translates to a significant investment costs for tractors in both systems – $27 million and $13 million for the round and rectangular bale systems, respectively. In the preprocessing facility system, tractors were only used for loaders, mowers, and rakes. The investment cost for tractors was just half of that in the rectangular bale system. However, an additional investment of $2.9 million in 84 tandem-axle trucks was needed to accommodate the forage choppers in the preprocessing system. Thus, the total harvest vehicle investment also costs about $10 million for the preprocessing facility system.

In the preprocessing facility system, a significant investment was allocated for one unit of industrial compactor/baler/wrapper, a building that covered the preprocessing facility and holding area for chopped LCB, and 15 acres of land in each of the three preprocessing zones in Figure 1. The total investment of the preprocessing equipment and land costs more than $6 million, accounting for more than 30 percent of total investment cost. If the investment in vehicles was shared by other operations or not included in the total capital costs, the preprocessing facility system was certainly the capital intensive logistic option among those three evaluated systems. However, with all equipment and vehicles being considered, the conventional round and rectangular bale methods surprisingly required a higher overall capital investment than the preprocessing facility system (Table VI).

Conclusions

This study analyzed the cost of various logistic methods of switchgrass, ranging from conventional hay methods to capital intensive preprocessing option, using capital budgeting analysis. Results suggest that the preprocessing facility system outperformed conventional hay methods in terms of the delivered cost to the biorefinery under Tennessee production conditions. Although the capital cost in equipment and land was significant, the savings in harvest and transportation costs and dry matter losses for the preprocessed bale system offset the extensive capital costs in preprocessing facility and generated a cost advantage over conventional hay methods.

Farms in Tennessee are small relative to the rest of the USA, have limited resources, and primarily have large round bale equipment available for switchgrass harvest. The analysis indicates that traditional hay systems may not be the most cost-effective way to procure switchgrass feedstock for a refinery and may limit farmer participation in the feedstock value chain. However, a feedstock cooperative that provides harvest, preprocessing, storage, equipment rental, and other services that may allow farmers to participate in a greater proportion of the feedstock value chain. The cooperative could potentially provide seasonal employment of farmers during the switchgrass harvest season, which does not conflict with other cropping activities. In addition, the cooperative could give farmers a mechanism for pooling capital, reducing risks, and potentially providing a higher rate of return on farmer resources. Programs to promote small farmer investment in feedstock cooperatives could potentially enhance rural economic development in Tennessee and the southeastern USA.

A caveat for this analysis is that the potential yield of ethanol per ton of dry matter was assumed to be the same regardless of storage method. Switchgrass dry matter that is not protected from weathering may potentially reduce the yield of ethanol. Also, due to a lack of data, the costs of debaling and grinding at the biorefinery were not explicitly accounted in this analysis. The different densities between large round and rectangular bales and preprocessed bales may create difference in grinding costs. Those hypotheses and the impact on costs are subject to examination in the future study. Finally, optimal biorefinery size depends on the tradeoffs among plant scale economies, transportation costs, and feedstock costs as determined by the costs of bidding land away from other agricultural enterprises with more LCB acreage being planted in a given draw area. Thus, another limitation of this analysis is the assumption of a given biorefinery size of 25 million gallons per year and a feedstock draw area of 50 miles. Given the potential feasibility of satellite preprocessing facilities, the next step would be the development of a biorefinery and feedstock operation model that considers these tradeoffs.

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About the authors

James A. Larson is an Associate Professor at the Department of Agricultural and Resource Economics, The University of Tennessee, Knoxville, Tennessee. James A. Larson is the corresponding author and can be contacted at: jlarson2@utk.edu

Tun-Hsiang Yu is an Assistant Professor at the Department of Agricultural and Resource Economics, The University of Tennessee, Knoxville, Tennessee.

Burton C. English is a Professor at the Department of Agricultural and Resource Economics, The University of Tennessee, Knoxville, Tennessee.

Daniel F. Mooney is a Research Associate at the Department of Agricultural and Resource Economics, The University of Tennessee, Knoxville, Tennessee.

Chenguang Wang is a former MS Graduate Research Assistant at the University of Tennessee, Knoxville, Tennessee and is currently a PhD Graduate Research Assistant at Michigan State University, East Lansing, Michigan.