Effect of Outdoor Storage Losses on Feedstock Inventory Management and Plant-Gate Cost for a Switchgrass Conversion Facility in East Tennessee

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Manuscript accepted for publication in *Renewable Energy*

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Abstract

Little is known about the potential impacts of storage losses on the optimal design of a switchgrass (*Panicum virgatum*) supply chain for an ethanol conversion facility. This study analyzed how storage losses impact plant-gate cost and feedstock inventory management for a 94,635 kL year⁻¹ switchgrass-based ethanol conversion facility in East Tennessee. A spatially-oriented, mixed-integer mathematical programming model was used to analyze plant-gate cost and harvest, storage, and delivery schedule for switchgrass packaged in large round or rectangular bales. Results indicate that *last in, first out* inventory management of feedstock minimized plant-gate cost. The key factor influencing inventory management was dry matter loss increasing at a decreasing rate with time in storage and distance of switchgrass production from the conversion facility. Our findings imply that the conversion facility can optimize the feedstock inventory and delivery management through coordinating the timing and location of switchgrass harvest with storage and delivery.

Keywords: harvest, lignocellulosic biomass, GIS, cost optimization, storage

Abbreviations: dry matter, DM; lignocellulosic biomass, LCB; geographical information system, GIS

1. Introduction

Development of a bio-based fuel, power, and product industrial sector in the United States has been a major policy focus at the federal and state levels. The Energy Independence and Security Act of 2007 mandates a minimum of 136 million kL year⁻¹ of renewable fuels for vehicles in the United States by 2022 [1]. To meet the aforementioned mandate, lignocellulosic biomass (LCB) from dedicated energy crops, agricultural residues, forest resources, and other bi-products will need to be produced on a cost competitive basis with fossil fuel sources [2]. Estimates suggest that up to 10% of agricultural land in the United States could be converted to dedicated energy crop production [2,3]. The southeastern U.S. has high potential to be the largest producer of least-cost LCB from dedicated energy crops such as perennial switchgrass (*Panicum virgatum*) of any region of the United States [4].

In 2007, the state of Tennessee invested \$70 million in the Tennessee Biofuels Initiative to encourage development of a renewable fuel sector in the state [5]. Genera Energy LLC, a for-profit company formed by The University of Tennessee, and DuPont Cellulosic Ethanol joined together to start operating a 0.32 kL year⁻¹ ethanol pilot refinery in Vonore, TN using corncocks, corn stover, and switchgrass as feedstocks in January 2010. The Initiative also contracted with 61 farmers to establish about 2,000 ha of switchgrass on farm fields within an 80 km radius of the pilot refinery. In addition, the Biomass Innovation Park in Vonore, TN was established to evaluate alternative harvest, storage, preprocessing, and pretreatment methods for LCB feedstock in 2011 [6]. Switchgrass from the farm fields is being used by the pilot biorefinery and the Biomass Innovation Park for research. Depending on market conditions and the success of the pilot plant in Vonore, a commercial facility may be developed and switchgrass area in East Tennessee expanded to supply the facility [6].

Perennial switchgrass was chosen by the Initiative because it is well adapted to the humid subtropical climate of Tennessee and the southeastern U.S. Switchgrass is capable of producing high LCB yields on soils not suited to row crop production, and can be harvested using standard hay equipment owned by many farmers [7,8]. These characteristics are believed to give switchgrass a competitive advantage over other potential feedstocks in the region [4]. One of the factors influencing whether switchgrass production for biofuels will be sustainable is how often feedstock is harvested. A production system that harvests mature switchgrass once after senescence has the potential to maximize the yield of sugars available for conversion to a biofuel [7,9]. The single harvest system may also minimize the removal of nutrients and the need for their replacement [7,9]. However, the need for storage increases with the single harvest system [10]. By comparison, harvesting feedstock twice a year (summer and fall) would nearly double nutrient requirements, provide equivalent LCB yields, and reduce total harvest and storage costs with a coordinated harvest system [11-14]. However, the quality characteristics of switchgrass are affected by the timing and frequency of harvest and thus the harvest plan will likely be related to the end use of the feedstock and the conversion technology [15].

Costs associated with the harvest, storage, and transportation of LCB such as switchgrass to a conversion facility have been identified as a barrier to the development of a sustainable LCB supply chain in the southeastern U.S. [16]. One important issue is the outdoor storage of switchgrass after harvest and before delivery to the conversion facility. Exposure of feedstock to weathering and losses of dry matter (DM) may adversely affect the quantity, quality, and cost of feedstock delivered to the conversion facility [10]. The potential tradeoffs among the costs of outdoor storage, DM losses, and the value of managing those losses through inventory management in a feedstock supply chain have only been examined on a limited basis [e.g., 17-

23]. While there is a substantial literature examining costs in a potential LCB feedstock supply chain, the potential interactions among harvest, storage, and transportation activities and their effects on feedstock inventory management to limit DM losses and minimize plant-gate costs have not been evaluated in the LCB feedstock supply chain literature (Table 1).

If the production of switchgrass for ethanol production is increased to meet the needs of commercially scaled ethanol production in East Tennessee, information will be needed about the least-cost methods of delivering switchgrass to a conversion facility considering the aforementioned supply chain management issues. Thus, our research objectives are: 1) to assess the impact of storage DM losses for alternative harvest methods on plant gate feedstock costs for an ethanol conversion facility that uses switchgrass harvested once a year after senescence and 2) to evaluate the potential effects of storage losses on harvest and feedstock inventory management for a once a year harvest system.

2. Review of Literature

Several important factors influence the economics of harvesting mature switchgrass. First, weather may limit field days to harvest feedstock and may be an especially important factor influencing plant-gate costs for switchgrass harvested in fall and winter [24]. Sunlight and temperature for field drying of feedstock is limited during this period giving fewer hours over which to harvest and spread fixed equipment costs [10]. Given the large amounts of LCB required for a conversion facility, most storage is projected to occur outdoors either on-farm or at a satellite location [25]. Harvested switchgrass stored outdoors is subject to rain, ultraviolet rays, and fluctuations in temperature and humidity that cause DM losses and is influenced by the methods used to harvest and store the feedstock and time in storage [26]. Switchgrass is currently

harvested using standard hay equipment, and this method is likely to remain until more specialized harvest equipment is developed for LCB [10].

Second, the narrow harvest window coupled with year-round demand for LCB by conversion facilities means that storage and inventory management of feedstock will be a critical management issue. Currently, our knowledge is limited about the impacts of storage DM losses for alternative harvest and outdoor storage systems on harvest and storage management and the cost of feedstock at the plant-gate (Table 1). Storage losses increase plant-gate costs because more area is devoted to feedstock production to meet the annual demand by the conversion facility [19,20,21]. The choice of harvest method (e.g., bale shape) influences outdoor storage losses which are higher for rectangular bales than for round bales [26,27]. Thus, tradeoffs among larger storage losses and lower harvest, storage, and transportation costs for rectangular bales when compared to round bales influence plant gate cost [26]. The timing of storage losses may also influence decisions to manage inventories of stored switchgrass given that DM losses may be the largest early on in storage, i.e., losses increase at a decreasing rate with time in storage [26]. The two aforementioned issues may be particularly important in the humid subtropical climate in Tennessee and the southeastern U.S. where switchgrass stored outdoors may be subject to more weathering [26]. In addition, DM losses may not only affect plant-gate costs but also greenhouse emissions and thus may be an important component in Life Cycle Assessment (LCA) analyses of biofuels production from LCB [28].

Third, plant-gate costs of switchgrass may be influenced by the geographically dispersed and relatively complex landscapes upon which crops are grown in Tennessee, when compared to other regions such as the mid-continental U.S. Average feedstock cost at the plant-gate is a function of the density of feedstock production in a potential draw area [29]. Feedstock density

has been defined as the proportion of land in the potential draw area that can be converted into feedstock production [30]. For a given conversion facility capacity, a lower density of production and thus a larger feedstock draw area means longer distances to move feedstock and increased plant-gate costs [31]. Given the geographical complexity of the landscapes in Tennessee, the degree of winding (i.e., tortuosity) in the road system in a potential feedstock draw area also influences plant-gate costs [32]. In many feedstock logistics studies, road distance is calculated as a straight-line, farm-to-plant distance with or without a winding factor (Table 1). The simplified models assume a circular collection area with the plant at the center and uniformly distributed farmland; discrete locations of production are not considered [29]. Thus, these simplifying assumptions may not be appropriate in areas with a more complex geography such as Tennessee. In addition, the availability of roads to move feedstock and industrial parks to place a conversion facility relative to available land for feedstock production have received little attention in the literature (Table 1).

Finally, the opportunity cost of agricultural lands to be potentially diverted from current agricultural activities (i.e., existing profitability of pasture, hay, and crop activities) also influences plant-gate feedstock costs [4,18,19]. Switchgrass is expected to be grown primarily on lands that are currently in low biomass yielding pasture and hay activities that have low profitability and thus a low opportunity cost for conversion to switchgrass production [4]. Thus, the concentrated availability of low opportunity cost land for conversion to switchgrass production can have a major impact on where a conversion facility may locate. The aforementioned factors that potentially influence the plant-gate costs of switchgrass harvested in fall and winter were incorporated into a spatially-oriented, mixed-integer mathematical programming model in the present study.

3. Modeling Framework

The Bioenergy Site and Technology Assessment (BeSTA) model is formulated as a single-year model (November through October production year). Similar to other feedstock supply chain models [18,19,33,34], harvest, storage, and transportation activities are sequenced on a monthly time-step to model the flow of feedstock to the conversion facility. Thus, the model is structured to provide within year dynamics in that switchgrass can be harvested in four months (November through February) and either delivered to the conversion facility or storage. Feedstock is delivered from storage to the conversion facility in the other eight months (March through October). While multi-year and stochastic models can provide insight into LCB feedstock production and logistic risks [17,21], the single-year formulation with inter-seasonal dynamics can provide important insights into potential feedstock supply chain operations and interactions [23].

The potential characteristics of the feedstock draw area considered in the analysis are: 1) available land resources for growing switchgrass, 2) the real road network for movement of feedstock, 3) available industrial parks for placement of a conversion facility, 4) opportunity costs for converting agricultural land to switchgrass production, 5) available field days for harvest from November through February considering weather, 6) bale shape and storage method (large round bale and large rectangular bale), 7) DM losses for alternative storage methods and time periods (months), and 8) farm and conversion facility requirements.

The conversion facility is assumed to contract with farmers and landowners to produce switchgrass. In addition, the facility is assumed to be a price taker and thus has limited market power and no current barriers to entry or exit to the ethanol market. Thus, the objective function

for the profit-maximizing conversion facility is to minimize total feedstock cost at the plant-gate (TFC [\$]) for a given production capacity such that:

$$(1) \quad \text{Min.} \quad TFC^j = C_{production}^j + C_{harvest}^j + C_{storage}^j + C_{transportation}^j,$$

where C is cost of switchgrass supply chain operation (production, harvest, storage, and transportation) for conversion facility location j when it is chosen.

For conversion facility j , farmers and landowners are also assumed to maximize profit and thus their willingness to convert land from existing production activities to switchgrass production is influenced by the relative profitability (π) of the two activities:

$$(2) \quad \pi_k = P_k \times Y_k - PC_k, \text{ and}$$

$$(3) \quad \pi_s = P_s \times Y_s - PC_s,$$

where P is output price (\$ Mg⁻¹), Y is output yield (Mg ha⁻¹), PC is production cost (\$ ha⁻¹), k is the existing farming activity on the land, and s is switchgrass production. Setting $\pi_k = \pi_s$ and solving for the switchgrass price farmers and landowners are willing to convert agricultural land from existing production activities to switchgrass production yields the following breakeven price (BEP [\$ Mg⁻¹]) relationship:

$$(4) \quad BEP_k = \begin{cases} \frac{P_k \times Y_k - PC_k + PC_s}{Y_s} & \text{if } \pi_k \geq R; \text{ else} \\ \frac{PC_s + R}{Y_s} & \text{if } \pi_k < R \end{cases},$$

where R is the rental rate for pasture/hay land or crop land. Thus, the opportunity cost for growing switchgrass is the higher of the two potential alternatives for the land: 1) profit from the existing agricultural activity on the land [35], or 2) or the prevailing market rental rate that can be obtained for the land [36].

The production cost of perennial switchgrass (PC_s) includes opportunity cost, amortized cost of establishment, annual maintenance cost, and annual harvest cost as a function of switchgrass yield [10]. Therefore, the total production cost of switchgrass is:

$$(5) \quad C_{production}^j + C_{harvest}^j = \sum_{i=1}^I \sum_{k=1}^K \sum_{b=1}^B (BEP_{ikb} \times \sum_{m=1}^M XH_{ikbm}),$$

where i is a land resource unit in the potential feedstock draw area, k is the existing agricultural production activity in i , b is the harvest method, and XH is annual switchgrass production (Mg).

The parameter m is defined as 1=November, the beginning of the production year for the conversion facility, and 12=October, the end of the production year for the conversion facility. Harvest activities occur in months 1 through 4 and storage and delivery activities occur in months 1 through 12 in the model.

Harvested switchgrass is either delivered to the conversion facility for immediate processing after harvest or delivered to storage such that:

$$(6) \quad NXS_{ikbmt} = XH_{ikbm} - XTN_{ikbm},$$

where NXS is feedstock (Mg) placed in storage using protection method t in month m before delivery to the conversion facility, and XTN is feedstock (Mg) delivered directly to the ethanol refinery during harvest. The total cost of storage for each harvest system is the cost of protection γ_{ibt} (\$ Mg⁻¹) multiplied by feedstock placed in storage in each month of the harvest season:

$$(7) \quad C_{storage}^j = \sum_{m=1}^M \sum_{i=1}^I \sum_{k=1}^K \sum_{b=1}^B \sum_{t=1}^T \gamma_{ibt} \times NXS_{ikbmt}.$$

Storage DM losses increase the cost of feedstock at the plant-gate of a conversion facility [19,20,21]. DM losses by storage method are assumed to increase at a decreasing rate with

storage time (months) in the model [26]. Losses for each month in storage are defined as the difference between the cumulative storage DM losses in the current and previous months. DM losses increase the quantity of switchgrass required to meet the fixed monthly and annual demands for feedstock of the conversion facility, thereby increasing plant-gate costs. The additional feedstock required to be produced (AFP) to compensate for losses during storage is:

$$(8) \quad AFP_{ikbmt} = \sum_{m=1}^M \sum_{i=1}^I \sum_{k=1}^K \sum_{b=1}^B \sum_{t=1}^T (XS_{ikbmt} - XTO_{ikbmt}),$$

where XS_{ikbmt} is cumulative feedstock placed in storage (Mg) and XTO_{ikbmt} is switchgrass transported to the conversion facility after storage (Mg).

Finally, the total cost to transport feedstock to the conversion facility from the field during harvest and from storage during the rest of the production year was:

$$(9) \quad C_{transportation}^j = \sum_{i=1}^I \sum_{b=1}^2 \theta_{ib} \times \frac{(\sum_{m=1}^4 \sum_{k=1}^K XTN_{mipb} + \sum_{m=1}^8 \sum_{k=1}^K \sum_{t=1}^2 XTO_{mipbt})}{1 - DML_{trans}},$$

where θ_{ib} is the cost of feedstock transportation for harvest method b (\$ Mg⁻¹) from each land resource unit i to the facility, and DML_{trans} is the proportion of DM loss during transportation. The parameter, θ_{ib} , is calculated based on Mg hr⁻¹ of feedstock transported, which is affected by the weight per truck load of feedstock, the distance between the field and the facility on the real road network, and the speed of the semi-truck. Given the capacity of the hauling vehicle and the feedstock weight transported per hour by the vehicle, the costs of labor and the operating and ownership cost of semi-truck and trailer transport can be calculated. Loading and unloading costs of feedstock are also considered in θ_{ib} .

The model has four main sets of constraints related to feedstock production, harvest, storage, transportation activities; and constraints related to conversion facility feedstock processing activities. The two feedstock production constraints are: 1) land used to produce switchgrass is no greater than the available agricultural land in a land resource unit, and 2) the annual supply of feedstock cannot exceed production of feedstock based on switchgrass yields and harvested area. In addition, there are five harvest activity restrictions: 1) total feedstock harvested cannot be more than annual feedstock production, 2) monthly feedstock harvested in each land resource unit must equal total switchgrass yields based on harvested switchgrass area in the unit, 3) total monthly feedstock harvested is limited by available harvest hours, 4) feedstock harvest occurs from November through February, and 5) total machine hours for each harvest operation cannot exceed total available field hours.

Four constraints are included in the storage and transportation modules: 1) monthly feedstock harvested must be greater than feedstock shipped to the conversion facility after adjusting for transportation DM losses, 2) monthly feedstock harvested must be greater than feedstock placed into storage in each month of harvest season, 3) stored feedstock must be transported to the conversion facility from March through October, and 4) delivered feedstock cannot exceed feedstock in storage. In addition, monthly feedstock deliveries must meet monthly ethanol production capacity.

To regulate feedstock inventory flows in each month of conversion facility operation, four conditions are specified in the model: 1) feedstock is either sent to the facility or placed into storage after harvest, 2) cumulative storage of feedstock in the current month must equal feedstock stored in the previous month plus switchgrass newly stored in the current month during harvest season, and 3) cumulative storage of switchgrass in the current month must equal

feedstock stored in previous month less feedstock sent to the conversion facility from storage in the previous month during the off-harvest period. Further details on the constraints in the model are in Appendix A. All parameters and variables in the model are non-negative. The model was programmed using GAMS 23.6 and solved using CPLEX 11. Optimization results were exported to Excel and were displayed in maps using ArcGIS.

4. Data and Methods

4.1. Analysis Assumptions

The geographic region for determining the location and feedstock draw area for a commercial sized switchgrass conversion facility in the model is East Tennessee. The region is comprised of Monroe County, where the DuPont Cellulosic Ethanol pilot conversion facility is located, and 12 other contiguous counties (Anderson, Blount, Bradley, Cumberland, Knox, Loudon, McMinn, Meigs, Morgan, Polk, Rhea and Roane) in about an 80 km radius of Vonore, TN (Figure 1). A facility with an annual ethanol production capacity of $94,635 \text{ kL year}^{-1}$ was used to estimate the feedstock draw area within the region. The case study region and annual capacity assumptions were based on author discussions with executives of Genera Energy LLC and DuPont Cellulosic Ethanol. The assumed potential size of a commercial LCB ethanol conversion facility in East Tennessee is similar in size to a $104,099 \text{ kL year}^{-1}$ corn stover facility planned in Iowa [37]. Switchgrass feedstock of $300,446 \text{ dry Mg year}^{-1}$ is required by the conversion facility based on an ethanol conversion rate of 317 L Mg^{-1} [38].

Total available field hours assumed for harvest operations is 325 hours with 86 hours in November, 82 hours in December, 78 hours in January and 79 hours in February [10]. Available field hours are based on 30 years of daily weather and daylight hour data for Knoxville, TN. Yields for standing lowland switchgrass after maturity and before harvest were assumed to not

decline during the four month harvest period. Available studies that evaluated standing yield losses after maturity are for upland switchgrass grown in Minnesota and Pennsylvania [15,39]. Lodging and matting of switchgrass from heavy snow negatively impacted yields of mature switchgrass harvested in April or May when compared with switchgrass harvested in October or November in Pennsylvania [15]. Yields in the Minnesota study did not differ between fall or spring harvest [39]. The case study area evaluated in this paper has a warmer climate with minimal snowfall that melts quickly than found in the aforementioned studies areas.

The switchgrass harvest, storage and transportation activities assumed in the model are as follows. Feedstock is mowed, raked, and baled using either round bales ($1.2\text{ m [diameter]} \times 1.5\text{ m [width]}$) or rectangular bales ($1.2\text{ m} \times 1.2\text{ m} \times 2.4\text{ m}$) wrapped with twine. Except for feedstock directly delivered to the conversion facility for processing during harvest, remaining feedstock is moved to the edge of the field using tractors and loaders/bale spears for storage before shipment to the facility on a semi-tractor trailer. Following storage, feedstock is loaded using tractors and loaders/bale spears and transported to the conversion facility using semi-truck trailers (38 large round bales or 24 large rectangular bales). Feedstock storage protection methods evaluated in the model are: 1) round bales placed on wooden pallets and covered with a tarp, and 2) rectangular bales placed on wooden pallets and covered with a tarp [10]. DM losses for harvesting and handling of feedstock before storage were assumed to be the same for both bale harvest methods and thus not accounted for in the analysis. Monthly storage DM losses for covered round and rectangular bales were calculated in the model using the Mitscherlich-Baule functions estimated by Mooney et al. [26]. The functions impose diminishing losses with time in storage and an asymptotic maximum DM loss for covered round $1.2\text{ m [diameter]} \times 1.5\text{ m}$

[width]) and rectangular bales ($1.2\text{ m} \times 1.2\text{ m} \times 2.4\text{ m}$) wrapped with twine. Assumptions for transportation DM losses were obtained from Sokhansanj et al. [25].

4.2. GIS Data

The 13-county region was disaggregated into a vector database of 1,044 contiguous 13 km^{-2} hexagons (i.e., land resource units) using high resolution remote sensing data from the U.S. Department of Agriculture National Agricultural Statistics Service 2010 cropland data layer database [40]. Public lands were excluded from consideration for conversion to switchgrass production. The land resource units are the geographic units used to model existing agricultural activities. The activities modeled for the region were corn [*Zea mays* L.], hay and pasture, soybean [*Glycine max* L.], winter wheat [*Triticum aestivum* L.], and switchgrass production. Crop yields were based on 2006 through 2010 county-level yields from the U.S. Department of Agriculture National Agricultural Statistics Service [41]. County-level switchgrass yields were obtained from the Oak Ridge National Laboratory Crop Database [42]. County-level yields were adjusted to soils to each land resource unit using yield indices created from potential crop yields by soil type from the U.S. Department of Agriculture Natural Resources Conservation Service SSURGO database [43]. Area for each agricultural activity in each land resource unit was determined from the cropland data layer database for 2010 [41].

The street-level, real road network from the U.S. Census Bureau [44] was overlaid on the land resource unit map to estimate transportation costs of switchgrass from the field to facility (Figure 1). The feedstock hauling distance from the field to the conversion facility was calculated as the distance between the center point of the land resource unit in which feedstock is produced and the center point of the land resource unit where the conversion facility is located. A hierarchy based on the speed limits of each type of road was used when generating the routes

between points to locate the most accessible routes: 1) primary/major roads, 2) secondary roads, 3) local and rural roads, and 4) other roads. The potential location of the conversion facility was assumed to be in one of 163 candidate industrial parks in the region with transportation and other infrastructure to support the facility. Locations of vacant land in industrial parks from a database developed by the Tennessee Valley Authority were digitized and overlaid on the map of land resource units [45] (Figure 1).

4.3. Price and Cost Data

Rental rates for pasture and non-irrigated crop land for 2010 that served as a floor on opportunity costs [Equation (4)] were from U.S. Department of Agriculture National Agricultural Statistics Service [46]. Rental prices in the region ranged from \$74 ha⁻¹ to \$175⁻¹ ha for non-irrigated crop land and \$36 ha⁻¹ to \$52⁻¹ ha⁻¹ for pasture and hay land. Prices for hay (\$83 Mg⁻¹), corn (\$191 Mg⁻¹), soybean (\$ 426 Mg⁻¹), and wheat (\$189 Mg⁻¹) in the 2010 crop year [47] were used to calculate opportunity costs for existing production activities for the calculation of breakeven switchgrass prices in the model. Crop budgets used to calculate opportunity costs are from The University of Tennessee Agricultural Policy Analysis Center's Agricultural Budgeting System [48]. Production costs were adjusted to 2010 dollars for consistency. Costs of production budgets for switchgrass for Equation (4) were estimated using budgets produced by The University of Tennessee Department of Agricultural and Resource Economics [10,26,34,49]. The budgets describe the field operations, equipment, materials, and labor for the establishment, annual maintenance, harvest, storage, and transportation of switchgrass. The production costs in the mathematical programming model were calculated in accordance with the American Agricultural Economics Association Cost and Return Handbook [50] and American Society of Agricultural and Biological Engineers Standards [51].

To calculate total switchgrass harvest and handling costs in the model, the assumed feedstock throughput rates for round and rectangular balers were 4.99 and 10.89 dry Mg hour⁻¹, respectively [10]. The costs of moving bales to the edge of the field with a tractor and loader/bale spear were assumed to be the same on a \$ dry Mg⁻¹ basis for both bale types (i.e., one rectangular bale or two round bales per trip) even though there may be cost advantages with the handling of rectangular bales [14]. Thus, baling and handling costs varied by switchgrass yields in each land resource unit in the model. Machine times for mowing and raking were assumed not to vary with yield [34]. Transportation costs include labor, operating, and ownership costs of tractors and loaders/bale spears used for loading and unloading of bales, and semi-trucks with trailers used for transporting bales from the field to the conversion facility. Cost for semi-trucks and trailers was calculated using estimated travel distances from the real street network between land resource units in the model.

5. Results

5.1. Feedstock draw area

The optimal location of the conversion facility as determined by BeSTA model was the same for the large round bale and the large rectangular bale systems (Figure 2; Table 2). It is in an industrial park near Interstate 75 in Sweetwater, TN in northwest Monroe County. The site is about 33 km west of the pilot ethanol facility in Vonore, TN. The feedstock draw area is arrayed along Interstate 75, a major north-south highway in the Tennessee River Valley, and stretches from south of Knoxville, TN on the northeastern end to south of Sweetwater, TN on the southwestern border (Figure 2). The siting of the conversion facility was influenced by the high concentration of low opportunity cost pasture and hay land in the Tennessee River Valley. More

than 98% of the land converted to switchgrass production was from pasture and hay production with the balance in wheat, soybeans, and corn (Table 2).

Results also indicate that the feedstock draw area was influenced by the geography of the region. The northeastern and southeastern edges of the draw area butt up against the Little Tennessee River/Tellico Lake and the foothills of the Great Smoky Mountains and the northwestern perimeter of the draw area borders the Tennessee River/Fort Loudon Lake/Watts Bar Lake. Average travel distances for shipping feedstock from the outer most land resource units to the conversion facility are within 38 km. Road access from the potential switchgrass producing land resource units to candidate industrial parks was also a factor in the location of the conversion facility (Figures 1 and 3). Truck volumes to move feedstock were more concentrated on routes near the conversion facility (Figure 3).

Notwithstanding the major geographical features of the region, the feedstock draw area has a relatively circular shape that is consistent with a stylized feedstock draw area used in the literature [29]. However, the geographical features of the region suggest that with a larger conversion facility, the feedstock draw area would likely have a more oblong shape following south on Interstate 75 and possibly a different location for the conversion facility depending on available industrial park lands and agricultural lands. A larger plant size may also influence the location of the facility. Because storage losses were larger for the rectangular bale system, switchgrass area for the rectangular bale system was 6% (933 ha) larger than for the round bale system to make up for the larger storage losses (Table 2; Figure 2).

5.2. Plant-gate costs

Results indicate that packaging switchgrass in large rectangular bales was the least cost system even though storage losses were higher than for switchgrass in large round bales (Table 2).

Storage losses were almost three times larger for rectangular bales (32,498 dry Mg) than for round bales (11,382 dry Mg) (Table 3). Increased production and opportunity costs of \$291,155 (6% higher) were directly proportional to the larger storage DM losses of 1,915 dry Mg (6% higher) in the model. Notwithstanding the larger storage losses, plant-gate costs for rectangular bales (\$77 dry Mg⁻¹) were 7% lower than for round bales (\$83 dry Mg⁻¹). Lower harvest, storage, and transportation costs in total more than offset the 6% higher switchgrass area required to compensate for the larger storage losses. The largest savings in rectangular bale costs, when compared to round bale costs, were for transportation (18% less), storage (10% less), and harvest (7% less) costs.

5.3. Monthly harvest, storage, and delivery schedule

The optimal monthly harvest schedule was influenced by storage losses, time in storage, and distance of the land resource unit from the conversion facility (Figure 2). Given that storage losses increased the amount of feedstock production needed to meet the fixed annual demand of the conversion facility, the BeSTA model minimized the additional production cost (i.e., minimized storage losses) by managing stored switchgrass inventory through the scheduling of monthly harvest and monthly delivery of feedstock to the conversion facility. Switchgrass designated for immediate delivery to the conversion facility during harvest was harvested on land resource units in the center of the feedstock draw area (hatched areas in Figure 2). Feedstock designated for storage by month of harvest exhibited a similar concentric bull's eye target pattern as found for the month of harvest. Switchgrass harvested in November and designated for storage was harvested on land resource units on the outer perimeter of the feedstock draw area (red colored hexagons). Switchgrass harvested in December made up the next most outer circle of the feedstock draw area (brown colored hexagons). Switchgrass

harvested in January (yellow hexagons) and February (green hexagons) were located closer to the conversion facility than feedstock harvested in November and December.

Results also indicate that *last in, first out* inventory management for stored switchgrass delivered to the conversion facility during the off-harvest period (March-November) minimized plant-gate costs (Figures 3 and 4). March deliveries out of storage to the conversion facility came from feedstock harvested primarily in February (Figures 2 and 3). Feedstock delivered in each month thereafter came from land resource units that were successively further away from the conversion facility and were harvested earlier during the November-February period. Thus, switchgrass deliveries illustrated in Figures 3 and 4(a) for the round and rectangular bale systems have a similar concentric bull's eye target pattern observed with harvest area designated for storage illustrated in Figure 2.

Storage losses that increased at a decreasing rate with time in storage were hypothesized to be the primary factor driving the *last in, first out* inventory pattern in the model. We tested this proposition by setting storage losses for the rectangular bale system to zero. The results presented graphically in Figure 4 indicate that the concentric pattern of monthly feedstock deliveries in Figure 4(a) disappeared and that no particular pattern is evident in feedstock deliveries over time in Figure 4(b). The inventory pattern observed for harvest, storage, and delivery appear to be driven by tradeoffs in minimizing transportation costs on the real road network and minimizing storage DM costs in the model.

6. Discussion

Several aspects of the results merit further discussion. First, outdoor storage losses are dependent on weather. Sanderson et al. [52] attributed differences in storage losses between two-single year studies conducted at similar locations to weather. The losses modeled in this study were obtained

from a 529 day storage study using twine-wrapped bales that were subject to weather conditions for 2008 and 2009 [26]. Thus, the level of storage losses under different weather conditions may vary from those modeled in this study. The level of storage losses may also change when using outdoor bale protection methods that are different from those used in this study (e.g., uncovered twine-wrapped or mesh wrapped round bales). However, we expect the same *last in, first out* inventory pattern would be observed under different weather and outdoor storage protection conditions if storage losses increase at a decreasing rate with time in storage.

Second, the finding that storage losses may influence optimal harvest scheduling implies that the conversion facility will coordinate the timing and location of harvest with storage and delivery. Our results complement Thorsell et al [14] who found that a conversion facility could reduce harvest costs using coordinated harvest machinery operations to maximize machinery and labor utilization. The coordination of feedstock supply chain involving many small farms will likely be more complicated when the size of the conversion facility increases, as suggested in Qualls et al. [51]. The findings in Qualls et al. [54] and the present study highlight the difficult logistical issues associated with the handling of switchgrass in a coordinated feedstock supply chain.

Two additional caveats should also be stated. First, the impact of weathering during storage on available sugars and biofuels yield dry Mg^{-1} were not considered in the analysis of the optimal harvest, storage, and delivery schedule. Mooney et al. [26] hypothesized that sugar losses from weathering during storage would magnify the negative effects of DM losses on plant-gate costs. Given this hypothesis, degradation of sugars during storage would reinforce the positive effects of *last in, first out* inventory management of feedstock. However, other research indicates that the mix of cellulose, hemicellulose, extractable sugars, and other characteristics of

switchgrass (e.g., lignin, extractables) may change negatively or positively with time in outdoor storage and may be influenced by storage cover, and other factors [53]. Thus, the potential tradeoffs between DM preserved and DM quality on harvest and inventory management and plant-gate costs should be further evaluated.

Second, our analysis does not consider the potential effects of inventory carryover between harvests on harvest, storage, and delivery management. Ebadian et al. (2011) [19] found that substantial carryover stocks may be necessary to relieve potential bottle necks at the conversion facility and to account for variable production caused by weather. These sources of uncertainty were not evaluated in this analysis. However, the findings potentially suggest that older feedstock would be carried over to the next year and new feedstock may be used first especially if storage losses increase at a decreasing rate over time as modeled in this study. The impact of storage losses on inventory carryover management in conjunction with harvest, storage, and delivery management also merits additional research.

7. Conclusions

This study analyzed the influence of outdoor storage loss on conversion facility plant-gate cost and feedstock inventory management for switchgrass harvested after senescence. A spatially-oriented, mixed-integer mathematical programming model using a monthly time-step was developed to analyze switchgrass harvest, storage, and delivery management. The model was used to evaluate feedstock logistics for a potential 94,635 kL year⁻¹ ethanol conversion facility in Tennessee. Switchgrass was packaged in large round or rectangular bales and delivered directly to the conversion facility or to outdoor storage for later delivery. Switchgrass in large rectangular bales was the least cost system even though storage losses were higher. Lower harvest, storage, and transportation costs more than offset the larger switchgrass area

required to compensate for higher storage losses. Thus, the delivered cost of rectangular bales at the plant gate was \$77 Mg⁻¹ or \$0.24 L⁻¹. Results also indicate that *last in, first out* inventory management during storage minimized plant-gate costs. The key factor driving inventory management was the relationship between storage losses and time in storage, i.e., dry matter losses increased at a decreasing rate with time in storage. Thus, the optimal inventory pattern observed for harvest, storage, and delivery was influenced by tradeoffs in minimizing transportation distance and minimizing storage losses. The optimal harvest scheduling pattern suggests that the conversion facility will coordinate the timing and location of harvest with storage and delivery. Future research should evaluate the impact of storage losses and feedstock quality on inventory carryover management in conjunction with harvest and delivery management for a switchgrass conversion facility.

8. Acknowledgements

The research was made possible with partial funding from U.S. Department of Energy project number DE-FG36-04GO14219 (UT Switchgrass Demonstration Project), 2009 Southeast Sun Grant/U.S. Department of Transportation Competitive Grant project number DT-OS59-07G00050, U.S. Department of Agriculture, Agriculture and Food Research Initiative Competitive Grant no. 2011-68005-30410 (Southeastern Partnership for Integrated Biomass Supply Systems), and U.S. Department of Agriculture, Cooperative State Research, Education, and Extension Service through Tennessee Hatch Project TEN00348.

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Table 1. Selected lignocellulosic feedstock supply chain optimizations studies that explicitly considered feedstock harvest, storage, and transportation logistics

Factor	Cundiff et al., 1997[17]	Tembo et al., 2003 [18]	Mapmepa et al., 2008[19]	An et al., 2011 [20]	Ebadian et al. 2011 [21]; Ebadian et al. 2013 [22]
Feedstock	Switchgrass	Native grasses, improved grasses, switchgrass, corn stover, wheat straw	Native grasses, improved grasses, switchgrass, corn stover, wheat straw	Switchgrass, wood residues	Wheat straw
Study Site	Virginia, USA	Oklahoma, USA	Oklahoma, USA	Texas, USA	Saskatchewan, CA
Spatial resolution	Not specified	County level	County level	County level, yields & costs not different across counties	Regional
Facility siting	Not considered	County level	Assumed Canadian County	County level	Assumed Prince Albert
Harvest Period	One & two cut yr ⁻¹ ; based on available field harvest days	Crop dependent	Crop dependent; based on available harvest days	Switchgrass, summer & fall; wood waste, continuous	Summer & fall—Aug-Oct
Method	Large round bales	Not specified	Large rectangular bales	Not specified	Large rectangular bales
Storage Method	Indoor, outdoor uncovered	At conversion facility, method not specified	Outdoor at field edge, covered	Indoor, anaerobic; outdoor, uncovered	Indoor, outdoor uncovered at field edge and satellite location
Losses	Monthly; differentiate between indoor, outdoor uncovered;	Assumed % loss mo ⁻¹ ; harvest & inventory management not evaluated	Assumed % loss mo ⁻¹ ; harvest & inventory management not evaluated; effect on feedstock draw area	Assumed % loss mo ⁻¹ ; harvest & inventory management not evaluated; effect on feedstock draw area	Assumed % loss yr ⁻¹ ; harvest & inventory management evaluated; effect on feedstock draw area
Transportation	Based on assumed truck cycle time in hr	Straight-line, county centroid	Straight-line, county centroid	Straight-line, county centroid	Straight-line
Feedstock flows	Harvest into storage; amount required; storage drawdown	Considered in model structure but not evaluated	Monthly harvest into storage	County of production to county of conversion	Harvest into storage; amount required; evaluated storage drawdown, carryover
Feedstock costs	Not include land opportunity costs	Include land opportunity costs	Include land opportunity costs; harvest compliment/costs based on available harvest days	Not include land opportunity costs	Not include land opportunity costs

Table 2. Optimal switchgrass conversion facility location and feedstock cost at the plant gate for the East Tennessee 13 county case study

Item	Large Round Bale System	Large Rectangular Bale System
Optimal conversion facility location (ID) ^a	438	438
Land use changes		
Pasture and hay land (ha)	14,895	15,998
Crop land (Wheat, Soybeans, and Corn) (ha)	231	82
Total (ha)	15,194	16,127
Switchgrass production (dry Mg year ⁻¹)	310,772	329,928
Storage dry matter losses		
Total (dry Mg)	10,326	29,482
Percentage of total (%)	3.32	8.94
Total plant-gate cost (\$ year ⁻¹)	25,196,285	23,152,473
Production (\$ year ⁻¹)	4,316,943	4,582,823
Opportunity cost (\$ year ⁻¹)	664,813	690,823
Harvest (\$ year ⁻¹)	12,812,666	11,938,467
Storage (\$ year ⁻¹) ^b	1,846,666	1,661,324
Transportation (\$ year ⁻¹)	5,201,641	4,279,760
Average plant-gate cost (\$ dry Mg ⁻¹)	83	77

^a Industrial park in Sweetwater, Tennessee, in northwest Monroe County and about 33 km west from the pilot ethanol facility in Vonore, Tennessee.

^b Opportunity costs for existing production activities for the calculation of breakeven switchgrass prices [Equation (4)] in the model were calculated using the following data. Rental rates that served as a floor on opportunity cost ranged from \$74 ha⁻¹ to \$175⁻¹ ha for non-irrigated crop land and \$36 ha⁻¹ to \$52⁻¹ ha⁻¹ for pasture and hay land [42]. Crop prices used to calculate crop profitability (2010 crop year) were: hay=\$83 Mg⁻¹, wheat= \$189 Mg⁻¹, soybean=\$426 Mg⁻¹, and corn=\$191 Mg⁻¹ [43]. Crop budgets (2010 \$) used to calculate opportunity costs are from The University of Tennessee Agricultural Policy Analysis Center's Agricultural Budgeting System [44].

Figure 1. East Tennessee 13-county case study area showing available land resource units available for the production of switchgrass, available industrial park locations for an ethanol conversion facility, and the major road network

Figure 2. Monthly harvest schedule for switchgrass annual harvest between November and February

Figure 3. Off-harvest season deliveries of covered large round bales from the switchgrass feedstock draw area to a $94,635 \text{ kL year}^{-1}$ ethanol conversion facility in East Tennessee

Figure 4. Comparisons of off-harvest season deliveries of covered large rectangular bales with dry matter loss (a) and without dry matter loss (b) from the feedstock draw area to an ethanol conversion facility in East Tennessee

Appendix A: Mathematical Programming Model Constraints

Production

$$(A1) \quad \sum_{b=1}^2 A_{ipb} \leq aa_{ip}, \quad \forall i, p$$

$$(A2) \quad XC_{ipb} \leq y_{ib} \times A_{ipb}, \quad \forall i, p, b$$

Harvest

$$(A3) \quad XC_{ipb} - \frac{\sum_{m=1}^4 XH_{mipb}}{1 - DML_{har}} \geq 0, \quad \forall i, p, b$$

$$(A4) \quad XH_{mipb} - y_{ib} \times AH_{mipb} = 0, \quad \forall i, p, b$$

$$(A5) \quad \sum_{i=1}^{1144} \sum_{p=1}^4 \sum_{b=1}^2 XH_{mipb} = \frac{CapUnit}{\lambda} \times rateava_m, \quad Dec \leq m \leq Feb, \forall m$$

$$(A6) \quad XH_{mipb} = 0, \quad Mar \leq m \leq Oct, \quad \forall m, i, p, b$$

$$(A7) \quad Numb_{mb} \times avehour_m - \sum_{i=1}^{1144} \sum_{p=1}^4 (mtb_{ib} \times AH_{mipb}) \geq 0, \quad \forall m, b$$

Transportation and Storage

$$(A8) \quad XH_{mipb} - \frac{\sum_{i=1}^I XTN_{mipb}}{1 - DML_{trans}} \geq 0, \quad \forall m, i, p, b$$

$$(A9) \quad XH_{mipb} - \sum_{t=2}^2 NXS_{mipbt} \geq 0, \quad Mar \leq m \leq Oct, \quad \forall m, i, p, b$$

$$(A10) \quad XTO_{mipbt} = 0, \quad Nov \leq m \leq Feb, \quad \forall m, i, p, b, t$$

$$(A11) \quad XS_{mipbt} - \frac{XTO_{(m+1)ipbt}}{1 - DML_{trans}} \geq 0, \quad \forall m, i, p, b, t$$

Conversion Facility Demand

$$(A12) \quad \lambda \left(\sum_{i=1}^{1144} \sum_{p=1}^4 \sum_{b=1}^2 XTN_{mipb} + \sum_{i=1}^{1144} \sum_{p=1}^4 \sum_{b=1}^2 \sum_{t=1}^2 XTO_{mipbt} XS_{mipbt} - Q_m \right) = 0, \quad \forall m$$

Inventory Flow

$$(A13) \quad \sum_{t=1}^2 NXS_{mipbt} = XH_{\text{mib}} - \frac{XTN_{mipbt}}{1 - DML_{\text{trans}}}, \quad Nov \leq m \leq Feb, \quad \forall m, i, p, b$$

$$(A14) \quad XS_{(m+1)ipbt} = (1 - DML_{\text{stor}_{mbt}}) \times XS_{mipbt} + NXS_{(m+1)ipbt}, \quad Nov \leq m \leq Feb, \quad \forall m, i, p, b, t$$

$$(A15) \quad XS_{(m+1)ipbt} = (1 - DML_{\text{stor}_{mbt}}) \times XS_{mipbt} + \frac{XTO_{(m+1)ipbt}}{1 - DML_{\text{trans}}}, \quad Mar \leq m \leq Nov, \quad \forall m, i, p, b, t$$

Table A1. Definitions of Variables, Parameters and Subscripts in Constraints

Variables/ Parameters/ Subscripts	Unit	Definition
<i>A</i>	Ha	area of switchgrass produced annually
<i>AH</i>	Ha	area of switchgrass harvested monthly from November to February
<i>XC</i>	Mg	quantity of switchgrass produced annually
<i>XH</i>	Mg	quantity of switchgrass harvested monthly from November to February
<i>XTN</i>	Mg	quantity of switchgrass transported directly to the conversion facility after harvest from November to February
<i>NXS</i>	Mg	quantity of switchgrass newly stored monthly from November to February
<i>XS</i>	Mg	quantity of switchgrass stored monthly from November to October
<i>XTO</i>	Mg	quantity of switchgrass transported from storage to the conversion facility from March to October
<i>Numb</i>		number of equipment used in harvest
<i>Q</i>	L Mg ⁻¹	quantity of ethanol produced in each month
Parameters		
<i>aa</i>	Ha	cropland available in each hexagon for each crop
<i>Y</i>	\$ ha ⁻¹	switchgrass yield in each hexagon
<i>DMLhar</i>	%	dry matter loss during harvest
<i>DMLstor</i>	%	dry matter loss during storage
<i>DMLtrans</i>	%	dry matter loss during transportation
<i>Mtb</i>	hr ha ⁻¹	machine time per acre for each machinery
<i>avehour</i>	Hr	available average working hours of machinery in each month
<i>rateava</i>		ratio of harvest machine working hours in each month to total machine working hours
λ	L Mg ⁻¹	switchgrass-ethanol conversion rate
<i>CapUnit</i>	L yr ⁻¹	annual capacity of a biorefinery
Subscripts		
<i>m</i>		Month
<i>i</i>		locations of switchgrass production fields (land resource units)
<i>j</i>		location of the conversion facility
<i>p</i>		crops (hay, corn, soybean, wheat)
<i>b</i>		harvest method (rectangular baler, round baler)
<i>t</i>		storage protection method

Figure

Figure

Figure

Figure

(a) With storage dry matter losses

Land resource unit

(b) Without storage dry matter losses

Conversion facility