Analyzing the Economics Values of An Alternative Preprocessing Facility in the Biomass Feedstocks - Biorefinery Supply Chain[*]

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Abstract

It is generally believed that preprocessing procedure can reduce the transportation and storage costs of biomass feedstock for biofuel production by condensing the feedstock's size. However, the capital costs of preprocessing facilities could be significant in the feedstock logistics system. Applying a GIS and mixed-integer mathematical programming model, this study evaluates the economic values of a preprocessing technology, stretch-wrap baling, in the biomass feedstock supply chain for a potential commercial-scale switchgrass biorefinery in East Tennessee. Preliminary results suggest that the stretch-wrap baling equipment outperforms the conventional hay harvest methods in terms of total delivered costs. Although the densification process involves additional capital and operation costs, the total delivered costs of switchgrass for a 25-million-gallon per year biorefinery in the preprocessing system is 12% − 21% lower than various logistic methods using conventional hay equipments.

Key words: biomass feedstock, cellulosic biofuel, logistic costs, preprocessing technology

JEL Codes: Q16, D24

1. INTRODUCTION

Over the past decade, the U.S. government and stakeholders have actively promoted the development of bioenergy to reduce dependence on imported fossil oils and to enhance revenues of agricultural producers. Currently, the main focus of the development of bioenergy is to produce transportation fuels from lignocellulosic biomass (LCB) feedstocks such as perennial crops, crop residues, and logging residues. It is generally believed that the advantages of using LCB feedstock over the traditional crops for biofuel production include the potential larger quantities of feedstock supply, less demand for water and soil quality, lower life cycle greenhouse gas emissions, and less linkage to the food market (Carolan, Joshi and Dale 2007; English et al. 2006).

Despite those aforementioned advantages, various technical barriers associated with LCB feedstock are currently hinging the commercialization of the cellulosic biofuel industry. Among those obstacles, the significant costs related to harvest, storage, and transportation of LCB feedstock is one of the major challenges to the economic viability of a cellulosic biofuels industry. The bulky nature of LCB feedstock requires a sizeable storage space on farm or at satellite sites. For example, maintaining a one year supply of feedstock for a 50 million-gallon-per year commercial biorefinery would require a 32-feet-hight stack of 4’×4’×8’ rectangular switchgrass bales covering more than 100 acres of land (Brass 2011). In addition to the substantial storage space, it is difficult to harvest and transport such bulky feedstock in large volumes. Also, the potential for dry matter losses during storage of LCB feedstock reduce the quantity and quality of biomass, and increase the feedstock costs for the refinery (Larson and English 2009).

Due to the lack of commercialized cellulosic ethanol industry, the Environment Protection Agency (EPA) has revised down the mandate of cellulosic biofuel issued in the Energy Independence and Security Act in 2007 from 100 million gallons per year (mgy) to 6.5 mgy in 2010, and made another significant cut from 250 mgy to 6.6 mgy this year. It is apparent that a cost-effective supply chain of LCB feedstocks for biorefinery is crucial to accelerate the development of an economically viable cellulosic biofuels industry to meet national goals. Therefore, the objective of this study is to evaluate the costs of LCB feedstocks delivered to a commercial-scale biorefinery for alternative feedstock logistic system configurations. Specifically, the economic value of satellite preprocessing facilities in the feedstock supply chain for the biorefinery is analyzed because it is hypothesized that preprocessing facilities reduce the transportation and storage costs of LCB feedstock through densification of feedstocks and the reduction in storage dry matter losses when compared to traditional hay systems. However, the preprocessing facilities may involve high capital cost that could potentially offset the cost savings in transportation and storage of delivered LCB feedstock.

To address this research question, the paper proceeds as follows. Section 2 provides a brief summary of previous studies in evaluating biomass feedstock logistic systems, followed by the description of analytical framework, model and data in Section 3. Section 4 presents the estimation results, and we follow with concluding comments in the last Section.

2. LITERATURE REVIEW

The logistics of LCB feedstock production has quickly surfaced in the bioenergy literature because the substantial costs and technical barriers related to harvest, storage, and transportation of LCB create significant challenges to economic viability of the cellulosic biofuel industry. The estimated costs of transporting, handling and storing LCB feedstock, such as corn stover or switchgrass, can make up more than 32% of total delivered costs (Hess et al. 2009). In order to reduce the cost of LCB feedstock, prior research has examined various components in the biomass feedstock logistics system, such as storage method (Cundiff, Dias, and Sherali 1996, Sokhansanj and Hess 2009), storage duration (Kumar and Sokhansanj 2007, Wang 2009), hauling distance between the field and biorefinery (Bransby et al. 2005), and the capacity of biorefinery (Sokhansanj and Hess 2009). A survey of 54 refereed journal publications analyzing the logistics issues of bioenergy production, including harvest/collection, storage, transport, pretreatment, and system design is summarized in Gold and Seuring (2011).

Given that commercial-scale biorefineries will need sizeable storage for the LCB feedstocks, many recent studies evaluated the role of preprocessing or pretreatment for densification of LCB in feedstock supply chain. Sokhansanj and Turhollow (2004) found cubing process increases the density of corn stover and reduces associated transportation and storage costs, however the final delivered costs of corn stover cubes are still higher than conventional corn stover bales (including final grinding costs) due to the capital equipment and operation costs of cubing. Uslu, Faaij and Bergman (2008) focused on detailed technical-economic analysis of three key preprocessing treatments and concluded that those treatments have significant influences on the performance of bioenergy supply chain. In addition to evaluating the function and costs of a specific densfication process, some studies proposed a more comprehensive biomass supply chain system for potential commercial-scale cellulosic biofuels industry. Hess, Wright and Kenney (2007) offered a clear perspective of the supply chain for LCB including the cost summary of harvesting, storing, preprocessing and transporting feedstock. Sokhansanj, Kumar and Turhollow (2006) developed an Integrated Biomass Supply and Logistics (IBSAL) model to simulate switchgrass collection, storage, transport and preprocessing in a feedstock supply chain study. Carolan, Joshi and Dale (2007) developed a network of regional LCB preprocessing centers that include multiple functions for LCB feedstock, including clean, separate and sort elements, chop, grind, mix/blend, and moisture control. Bransby et al. (2005) estimated total delivery cost of switchgrass from field to biorefinery by yield, harvest method, hauling distance, and preprocessing technology by using an enterprise budget model to. Larson et al. (2010b) applied similar approach to evaluate alternative switchgrass logistic systems and suggested that a stretch-wrap baling system has potential advantage over the conventional hay system in terms of final delivered costs.

Those aforementioned studies clearly expand our knowledge of alternative LCB feedstock logistics systems; however, few studies have comprehensively evaluated different harvest, storage, and preprocessing options to minimize the overall logistic costs of LCB feedstock supply chain. Also, the dry matter losses issue during storage has been usually ignored in the previous studies, except for Larson et al. (2010b); hence underestimate the potential benefits of preprocessing procedure.

3. METHODOLOGY AND DATA

3.1 Analytical Framework

To evaluate the economic potential of satellite preprocessing facilities within a LCB feedstock supply chain, this paper extends Larson et al. (2010b) to analyze two LCB feedstock supply chain systems (see Figure 1). The system on the left side of Figure 1 only includes feedstock producers and a biorefinery without preprocessing procedures (hereafter referred to as baseline system). The baseline system, initially developed in Wang (2009), includes two conventional hay logistics options for LCB feedstock. The LCB feedstock can be harvested by large round baler, large square baler, or mixed square-round baler options, stored at the edge of the field with or without protection, and delivered to the biorefinery as needed throughout the year. The optimal logistic system including the location of biorefinery, feedstock collection area, harvest and storage schedule, and feedstock transportation is initially determined by minimizing the total delivered costs for a potential commercial-scale biorefinery.

In the second logistic system (the right portion of Figure 1), preprocessing procedure is added in the biomass supply chain in the baseline system (hereafter referred to as preprocessing system). Assuming the existence of the biorefinery, a stretch-wrap baler preprocessing technology to provide densification and protection of LCB feedstock before storage is considered in the analysis. The LCB feedstock is harvested by a chopper with rotary header, directly delivered to the preprocessing facility, baled in a more condensed form, wrapped by plastic for protection, stored on the site and delivered to the biorefinery as needed throughout the year. In addition to the feedstock collection area and schedule of harvest and storage, the location of preprocessing facilities is also determined through minimizing the delivered costs.

The value of incorporating the particular preprocessing technology is evaluated by comparing feedstock delivered costs in the preprocessing system with that in baseline system. If the preprocessing system outperforms the baseline in terms of the total delivered costs for a commercial-scale biorefinery, it suggests that the preprocessing system can potentially enhance the profit of the commercial-scale biorefinery. However, if the model does not suggest lower delivered cost associated with the preprocessing system, the benefit of additional feedstock densification process is limited.

3.2 Optimization Model and Data

The analytical engine of this study is a mixed-integer mathematical programming (MIP) model incorporating the data generated from a high-resolution GIS model. The integration of the mathematical programming and GIS models is designed to identify the LCB feedstock harvest area and optimal location of the biorefinery and satellite preprocessing facilities for feedstock based on the size of biorefinery, throughput of the preprocessing facilities, and the availability of biomass feedstock. The objective is to minimize total logistic cost (*TLC*) including production cost, harvest cost, storage cost and transport cost incorporating dry matter losses adjustment, subject to constrains on feedstock production, feedstock demand, and various logistics conditions. The model structure in the baseline system can be presented as follows (the definitions of variables and parameters can be found in Table 1):

(1) Min. TLC

$$= \sum_i \sum_p \sum_b \left(BEP_{ipb} \times XC_{ipb} \right) \qquad \text{(production and harvest cost)}$$

$+\sum_m \sum_i \sum_p \sum_b \sum_t \gamma_{ibt} \times NXS_{mipbt}$ (storage cost)

$+\sum_i \sum_b \theta_{ib} \times \frac{(\sum_m \sum_p XTN_{mipb} + \sum_m \sum_p \sum_t XTO_{mipbt})}{1-DML_{trans}}$ (transportation cost)

s.t.

(2) $\sum_b A_{ipb} \leq aa_{ip}, \ \forall\, i, p$ (acreages constraint for production)

(3) $XC_{ipb} \leq y_{ib} \times A_{ipb}\ , \ \forall\, i, p, b$ (yield constraint for production)

(4) $XH_{mipb} = 0\ , \ March \leq m \leq Oct\ \forall\, m, i, p, b$ (constraint on harvest month)

(5) $Numb_{mb} \times avehour_m - \sum_i \sum_p (mtb_{ib} \times AH_{mipb}) \geq 0\ , \ \forall\, m, b$

(constraint on harvest machine working hours)

(6) $XH_{mipb} - \frac{\sum_j^1 XTN_{mipb}}{1-DML_{trans}} \geq 0, \ \forall\, m, i, p, b$ (harvest and direct shipment balance)

(7) $XH_{mipb} - \sum_t^2 NXS_{mipbt} \geq 0\ , \ March \leq m \leq Oct\ \forall\, m, i, p, b$ (harvest and storage balance)

(8) $XS_{mipbt} - \frac{XTO_{(m+1)ipbt}}{1-DML_{trans}} \geq 0\ , \ \forall\, m, i, p, b, t$ (storage and shipment balance)

(9) $\lambda\left(\sum_i \sum_p \sum_b^2 XTN_{mipb} + \sum_i \sum_p \sum_b \sum_t XTO_{mipbt}\right) - Q_m = 0\ , \ \forall\, m$ (ethanol production)

Equation (1) is the cost-minimization objective function, while equations (2) and (3) present the restriction on the land acreage and yield for LCB feedstock in each unit area. Equations (4) and (5) constrain the harvest month and the harvest machine hours per month during harvest season, respectively. Equation (6) requires harvested feedstock in each month to be greater than the shipment to the biorefinery after adjusting the transportation dry matter losses, while the harvested feedstock tonnage each month should be greater than the amount of feedstock put into storage in equation (7). Equation (8) assures that feedstock delivered from storage cannot exceed available stocks in storage in each month. Finally, feedstock delivered to the biorefinery in each month should meet the demand for biofuel production by the biorefinery, imposed in equation (9). The model structure for the preprocessing system is similar except for the additional component of preprocessing cost in the objective function and associated capacity and transportation constraints.

The analysis is applied to a potential commercial-scale switchgrass ethanol refinery in East Tennessee. Switchgrass is considered as a strong potential energy crop for biofuel production in the U.S. since it is a native perennial grass. In addition, it presents various advantages of high yield and reliable productivity on poor soils, lower demand for fertilizer than field crops such as corn, high water use efficiency, and high tolerance of a wide range of environmental conditions (McLaughlin and Kszos 2005; Wright 2007). It is particularly ideal planted on the marginal pasturelands and croplands in the semi-humid and humid environments of the Southeastern region of United States. Thus, switchgrass is selected in the analysis.

There are total 13 counties included in the study area given their geographical connection with the pilot-scale cellulosic ethanol plant currently operated in Monroe County, Tennessee. Those counties are divided into five square-mile hexagons based on a remote sense data (Figure 2a), excluding the federal lands area. To determine the potential area for switchgrass, the breakeven price of switchgrass is generated to compare with the revenue of traditional crops activities, mainly hay, corn, soybeans and wheat, in each hexagon. In addition, the yield of switchgrass in each hexagon is varied due to soil type.

Based on Jackson (2010), the annual capacity of the biorefinery in this study is set at 25 million gallon per year. Applying a conversional rate of 76 gallons per dry ton (Wang et al. 1999), it implies that nearly 329,000 dry tons per year of switchgrass are required to meet this biorefinery that operates nearly year round. The harvest window for switchgrass is assumed between November 1 and March 1. Based on the weather condition in East Tennessee, a total of

53 days would be suitable for harvest operations during the four-month period and this translates into 325 hours available for harvest (Larson et al. 2010b).

It is assumed that, in both baseline and preprocessing systems, one-third of harvested switchgrass is directly brought to biorefinery during harvest season for ethanol production, while the remaining two-third of switchgrass is put storage. Storage cost incorporated in this study include the protection materials needed for storing bales on field, and the equipment and labor used for applying those materials and stacking bales. In the baseline system, the bales are assumed stored on the edge of the field, hence two options of top cover for bales are considered: covered by plastic tarp and uncovered. In addition, two options of bottom support for bales are evaluated: well-drained ground and wooden pallets. The storage cost associated with plastic tarp is estimated to be \$ 4.01/ton for round bale and \$ 2.59/ton for square bale; and the storage cost associated with wooden pallets is estimated to be \$ 4.07/ton for round bale and \$ 3.75/ton for square bale. The total storage cost varies depending on storage treatments which utilize different storage methods and surface protection methods. Dry matter losses for storage periods of up to 365 days is modeled for the conventional hay systems using Mitscherlich-Baule functional forms estimated using data from Larson et al. (2010a).

In the preprocessing system, the storage of preprocessed feedstock is at the site of preprocessing facility. The stretch-wrap baler in the preprocessing system was originally developed in Europe for processing garbage and is introduced in the U.S. for agricultural products. The technology can create a 3,000-lb (1.5-dry ton) condensed bale of switchgrass about the same dimensions as a conventional large round bale and the production throughput is about 45 tons per hour. 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 assure the flows of preprocessing operation, it is assumed that the 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. The parameters for calculating the ownership and operating costs of the equipments used for harvest, storage, preprocess and transportation in both baseline and preprocessing systems can be found in Table III in Larson et al. (2010b).

In order to generate precise travel distances from switchgrass fields to the biorefinery, the detailed road and rail networks, industrial parks, transmission lines, and other geo-spatial layers are incorporated from the GIS model, BioFLAME (Wilson 2009). The locations of biorefinery and preprocessing facilities are assumed to be located in 164 candidate industrial parks with construction and the access to transportation infrastructure (Figure 2b). The hauling distance from a field to the biorefinery is calculated as the distance between center point of the hexagon in which switchgrass is produced and the center point of the hexagon where the biorefinery is located. A hierarchy (primary/major roads > secondary roads > local and rural roads > other roads) based on the speed limits of each type of roads is used when generating the routes between points to locate the most accessible routes. The transportation cost is then measured by the hauling distance, driving speed, and vehicle capacity.

4. RESULTS

4.1 Baseline System

In the baseline system, four cases of different harvest and storage combinations for switchgrass are evaluated. Those four logistics cases include:

Case 1: 1/3 harvested by round baler & directly delivered to biorefinery during harvest season;
2/3 harvested by round baler & stored with protection for use during off-season

Case 2: 1/3 harvested by square baler & directly delivered to biorefinery during harvest season;
2/3 harvested by square baler & stored with protection for use during off-season

Case 3: 1/3 harvested by square baler & directly delivered to biorefinery during harvest season;
2/3 harvested by round baler & stored with protection for use during off-season

Case 4: 1/3 harvested by square baler & directly delivered to biorefinery during harvest season;
2/3 harvested by round baler & stored without protection for use during off-season

Cases 1 and 2 represent the sole large round bale and large square bale system, respectively. A large round bale, designed to shed water, can prevent dry matter losses more effectively than does a large square bale when stored outdoors (Cundiff and Grisso, 2008; Larson et al. 2010a). However, a larger throughput capacity of a large square bale may have harvest, handling, and storage economies of size advantages over large round bales (Thorsell et al., 2004; English et al., 2008). Hence, a combination of those two methods (using square bale for directly delivered feedstock during harvest window and using round bale for stored feedstock for off-season supply) in Cases 3 and 4 may strengthen the cost advantages of both methods. The difference between Case 3 and 4 is the storage protection on the round bales.

Table 2 summarizes the outputs of those four options in the baseline system. For a 25-mgy biorefinery, the sole round bale system (Case 1) has the highest delivered costs ($24.8 million), while the mixed system without storage protection (Case 4) is the most cost efficient method after incorporating the dry matter losses during storage ($22.3 million). The cost savings in storage materials, labors and equipments in the Case 4 offset the dry matter losses during the storage. For the other three cases with storage protection, the sole large square bale system (Case

2) is the most cost effective method, followed by the mixed system with storage protection (Case 3). Despite significant dry matter losses during storage (the difference between harvested and delivered tonnages), the economy of sizes in transportation for large square bales make this option cost effective comparing to other two cases. The average cost of those cases in the baseline ranges between $67 and $75 per ton.

The location of biorefinery and feedstock draw area in Case 3 is presented in Figure 3. The solved optimal location of biorefinery sits in the northwest Monroe County, which is very close to the location of the pilot-scale cellulosic ethanol plant by DuPont Danisco LLC in Vonore, Tennessee. The selected draw area of switchgrass is within 25 miles of the biorefinery. Since the large square bale has the advantage of transportation efficiency over the large round bales, the model selects large round baler to harvest switchgrass in those hexagons near the biorefinery, whereas the producers located further away from biorefinery can save delivered costs using large square baler.

4.2 Preprocessing System

The result of the logistics system incorporating the stretch-wrap baler for switchgrass densification is presented in Table 3. The total delivered cost of 328,947 tons of switchgrass is $19.6 million. The additional preprocessing cost ($5.3 million) accounts for nearly 27% of total delivered costs. The transportation cost of the chopped switchgrass directly delivered from the field to biorefinery (1/3 of total harvested switchgrass) during harvest season is about $1.4 million, while the other two-third of switchgrass for densification is under two transportation cost components: the shipping cost from filed to preprocessing facilities in a chopped form ($2.7 million), and the cost from preprocessing facilities to biorefinery in condensed-wrapped bales

($2.1 million). Applying the single-pass harvest procedure, the production and harvest cost for the chopped switchgrass is only $8.1 million for 335,661 tons of switchgrass.

Figure 4 illustrates the feedstock area and the optimal location of preprocessing facilities in the study area. Since we would like to evaluate the additional advantage (or cost) of adding preprocessing facilities in the baseline system, the biorefinery is then assigned to be in the same location as that in the baseline system. The feedstock draw area has slightly shifted to the northeast region into Blount County when preprocessing facilities are available in the feedstock logistics system. Given the throughput of the stretch-wrap baler, four units of the preprocessing facility are needed to meet the feedstock demand of biorefinery. Two units of preprocessing facilities are operated at full capacity (63,000 tons), while the other two facilities are utilized at about 75% of full capacity.

The delivered cost of switchgrass for a biorefinery with 25-mgy capacity in the preprocessing system is nearly 12% lower than the least cost case in the baseline system (Case 4). Moreover, the stretch-wrap baling system presents a 20% cost advantage over the sole large round baler case (Case 1). Interestingly, the logistic cost saving in the preprocessing system is primarily attributed to the single-pass harvest procedure. The condensed-wrapped bales present the cost advantages in transportation; however, the total transportation cost of harvested switchgrass including three components (field−biorefinery, field−preprocessing, and preprocessing−biorefinery) in the preprocessing system is still higher than any case in the baseline system. The cost comparison of those cases, however, does not explicitly consider potential differences among management structures and the associated costs and risks for those systems.

5. CONCLUSIONS

This study applies a MIP and GIS model to analyze the economic values of adopting an alternative preprocessing technology in the LCB feedstock supply chain for a potential commercial-scale biorefinery. Despite the capital investment and operation costs, the evaluated preprocessing system still presents advantage over the conventional hay system in terms of the total delivered costs. Comparing various cases under the baseline system with the evaluated preprocessing system, the stretch-wrap baling system improves the switchgrass logistics costs by 12% − 21% under Tennessee production condition.

The advantage of the preprocessing system in the LCB feedstock logistic system may be more significant when the size of biorefinery capacity increases. Additional cost saving is potentially achieved when more switchgrass is harvested and condensed. Also, the total delivered costs may reduce further in the preprocessing system when the location of biorefinery and preprocessing facilities can be jointly determined. In this study, the location of biorefinery in the preprocessing system is determined based on the location in the baseline system in order to illustrate the impacts of introducing preprocessing facilities in the feedstock logistic system for an existing biorefinery. When the constraint of the location of biorefinery is released, the biorefinery may be relocated and the optimal output can potentially improve.

Further research should continue to evaluate the dry matter losses or feedstock quality of those condensed-wrapped bales generated from the preprocessing system during storage. Also, exploring various options in harvest, storage, preprocessing and transportation in the LCB feedstock logistic system is necessary for enhancing the profitability of the industry. Particularly, exploring the economic values of combing various pretreatment and preprocessing procedures to generate a more densified feedstock with constant quality will provide useful information of a sustainable feedstock supply chain to this emerging industry.

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Table 1. Definition of Variables and Parameters for Biomass Feedstock Logistics Model

Variables/ Parameters/ Subscripts	Unit	Definition
Variables		
A	acre	acres of switchgrass produced annually
AH	acre	acres of switchgrass harvested monthly from November to February
XC	ton	tons of switchgrass produced annually
XH	ton	tons of switchgrass harvested monthly from November to February
XTN	ton	tons of switchgrass transported directly to the biorefinery after harvest from November to February
NXS	ton	tons of switchgrass newly stored monthly from November to February
XS	ton	tons of switchgrass stored monthly from November to October
XTO	ton	tons of switchgrass transported from storage to the biorefinery from March to October
Numb		number of equipment used in harvest
Q	gallon	quantity of ethanol produced in each month
Parameters		
BEP	$/acre	breakeven price of planting switchgrass as alternative of traditional crops
aa	acre	cropland available on in each hexagon for each crop
y	$/acre	switchgrass yield
DML_{har}	%	dry matter loss during harvest
DML_{stor}	%	dry matter loss during storage
DML_{trans}	%	dry matter loss during transportation
mtb	hour/acre	machine time per acre for each machinery
avehour	hour	available average working hours of machinery in each month
rateava		ratio of harvest machine working hours in each month to total machine working hours
Λ	gallon/ton	conversion rate of switchgrass to ethanol
CapUnit	gallon/yr	annual capacity of a biorefinery
Dd	gallon	monthly demand of ethanol

Table 2.Swithcgrass Delivered Cost under Various Harvest and Storage Options in the Baseline System

	Case 1	Case 2	Case 3	Case 4
	(1) Harvest season: Round baler - no protection (2) Off-harvest season: Round baler - tarp.pallet	(1) Harvest season: Square baler - no protection (2) Off-harvest: Square baler - tarp.pellet	(1) Harvest season: Square baler - no protection (2) Off-harvest: Round baler - tarp.pallet	(1) Harvest season: Square baler - no protection (2) Off-harvest: Round baler - non-tarp.ground
Total delivered cost	**$ 24,777,540**	**$ 23,468,530**	**$ 23,814,770**	**$ 22,292,400**
Production, harvest and staging cost	$ 17,353,720	$ 17,403,050	$ 16,840,410	$ 17,182,710
Storage cost	$ 1,881,202	$ 1,789,048	$ 1,881,202	$ -
Transportation cost from field to biorefinery	$ 5,542,611	$ 4,276,433	$ 5,093,158	$ 5,109,688
Total delivered cost ($/ton)	**$ 75.32**	**$ 71.34**	**$ 72.40**	**$ 67.77**
Total delivered switchgrass (tons)	**328,947**	**328,947**	**328,947**	**328,947**
Total harvested switchgrass (tons)	**346,881**	**383,041**	**346,881**	**353,738**

Table 3.Switchgrass Delivered Cost in the Preprocessing System

	(1) Harvest season: Chopped feedstock - no protection (2) Off-harvest: Condensed round baler - plastic wrap			
Total delivered cost	**$**	**19,606,780**		
Production and harvest cost	$	8,118,698		
Total transportation cost	$	6,210,636		
Field to biorefinery			$	1,411,704
Field to preprocessing facilities			$	2,699,968
Preprocessing facilities to biorefinery			$	2,098,964
Preprocessing and storage cost	$	5,277,445		
Variable cost			$	2,794,213
Fixed cost			$	2,483,232
Total delivered cost ($/ton)	**$**	**59.60**		
Total delivered switchgrass (tons)		**328,947**		
Total harvested switchgrass (tons)		**335,661**		
Total preprocessed switchgrass (tons)		**219,298**		

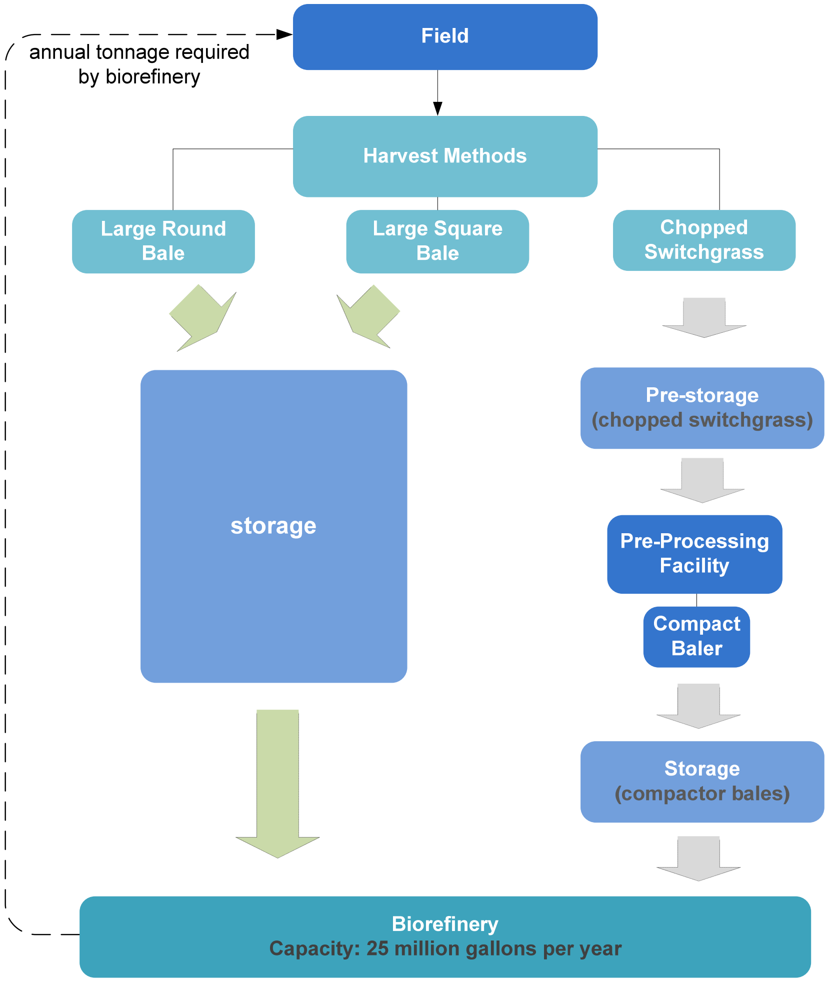

Figure 1. Evaluated biomass feedstock logistics systems

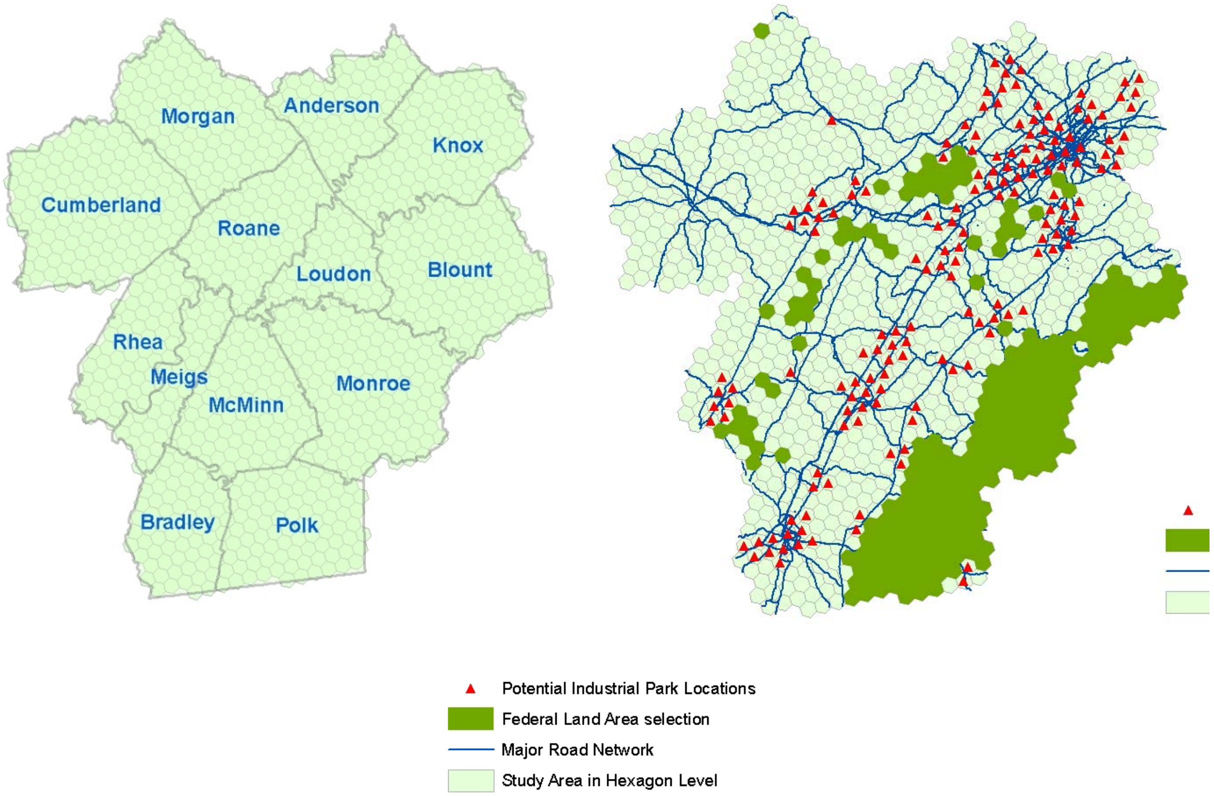

Figure 2. Study area of 13 counties in East Tennessee in hexagon level

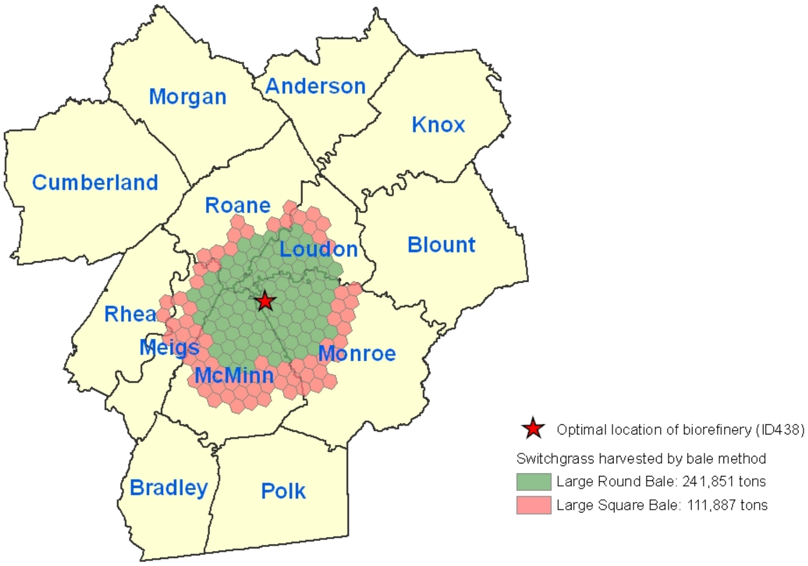

Figure 3. Location of biorefinery and switchgrass harvested area by baler in the optimal case (case 4) in the baseline system

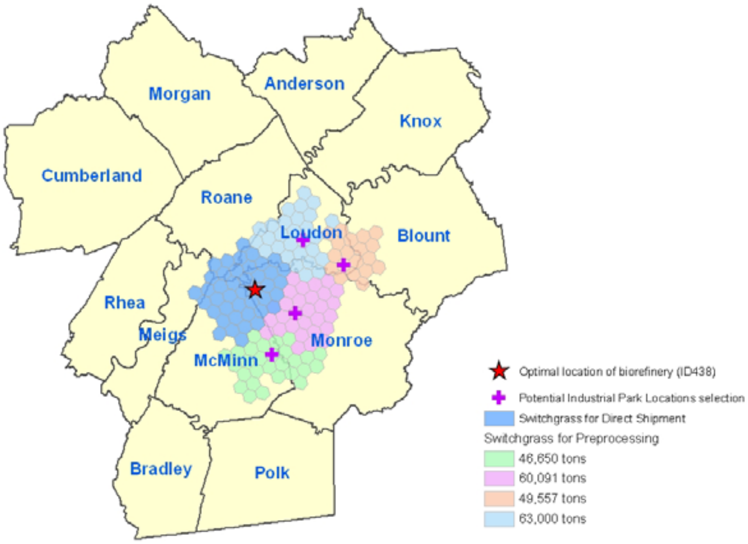

Figure 4. Location of biorefinery, preprocessing facilities and feedstock draw area in the preprocessing system