Evaluating the Impacts of Biomass Feedstock Transportation on Air Quality: A Tennessee Case Study

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ABSTRACT

The efficiency of supply chain system of lignocellulosic biomass (LCB) feedstock is crucial to the development of the cellulosic biofuel industry. Moreover, the potential environmental impact of LCB feedstock transportation has also received increasing attention lately. This study first applied a spatial-oriented mixed-integer mathematical programming model linked to a GIS resource model to generate a least-cost solution of alternative typical feedstock supply chain systems for a potential commercial scale biorefinery per year in east, central and west Tennessee. The EPA's MOVES model was then used to estimate the baseline emissions for 2010 in the study region and additional emissions generated from hauling feedstock. Results showed that switchgrass is more suitable than energy sorghum for biofuel production in Tennessee based on feedstock plant-gate cost and hauling emissions. Also, the large square bale system outperformed the large round bale system in both economic and environmental indicators. Finally, the biorefinery with the most economic feedstock cost and the least feedstock hauling emission is suggested to be sited in Robertson County, TN. The emissions of NO_x, CO_2, PM_{10}, and $PM_{2.5}$ from feedstock hauling in related counties increased by 0.12%, 0.04%, 0.15%, and 0.18%, respectively, when comparing with the emissions produced by existing overall traffics.

Keywords: lignocellulosic biomass, emissions, optimization, GIS

JEL code: C61, Q42, Q53

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EXECUTIVE SUMMARY

The development of a bio-based fuels and power sector using lignocellulosic (LCB) feedstocks is currently a major focus of bioenergy sector development in many states. Among others, the Tennessee Biofuels Initiative is a state sponsored initiative to develop an LCB-based value chain in Tennessee. As a part of the Initiative, a pilot biorefinery utilizing corn cobs and switchgrass in East Tennessee is being jointly operated by DuPont Danisco Cellulosic Ethanol LLC and Genera Energy LLC. Based on the success of the pilot biorefinery, the vision of establishing a commercial-scale biorefinery in the state in the near future has surfaced. With the much larger scale of a commercial sized biorefinery, the amount of LCB feedstocks that are produced on agricultural lands to supply the biorefinery will be considerable. Since most of those potential areas for LCB feedstock currently are either idle or used for other traditional crops that are less bulky than the LCB feedstock, the production of LCB feedstocks for the commercial scale biorefinery will create heavier traffic on roadways that link the fields and the biorefinery than for traditional agricultural activities. The increased traffic will produce extra vehicle emissions that may be an environmental issue if the air pollution is not considered and managed.

Given the potential for developing a cellulosic biofuel industry in Tennessee, this study evaluates the emissions produced from LCB feedstock hauling to the optimal sites of a biorefinery in several regions of the state that have the least plant-gate cost of feedstock. Our specific research objectives are: **1)** to develop a comprehensive estimate of vehicle emissions caused by delivery of LCB feedstock to a commercial-scale biorefinery site, and **2)** to evaluate tradeoffs in plant gate feedstock costs and hauling emissions for alternative biorefinery locations in Tennessee. Plant-gate costs and hauling emissions were evaluated for large round and large square bale harvest, storage, and transportation systems.

The analysis of plant-gate costs and hauling emissions to a biorefinery of two distinct LCB feedstocks, switchgrass (perennial grass) and energy sorghum (annual crop), is divided into two major steps. First, the least-cost feedstock draw area and location of the commercial-scale single-feedstock based biorefinery is identified for each of three regions in Tennessee (eastern, central, and western) by minimizing feedstock plant-gate costs through a spatial-oriented mathematical programming model. The cost-minimization output identifies the most efficient road links within the feedstock draw area to the biorefinery based on the real road network for each region. Second, the existing traffic emissions on the road networks and the additional emissions produced from feedstock transportation are estimated and evaluated by EPA's MOVES model using the vehicle traffic flow data generated in the first step.

The study results are summarized as follows:

- From an economic standpoint, switchgrass is more feasible as a feedstock when compared to energy sorghum for cellulosic biofuel production in Tennessee. The significantly higher plant-gate costs of energy sorghum are primarily driven by its estimated production costs. The inputs required to produce an annual crop, such as energy sorghum, are more than for switchgrass. Also, short of available crop land and the less fertile soil area, particularly in east Tennessee, generate a larger feedstock draw area, hence increasing transportation cost.

- In terms of the performance of the two evaluated supply chain systems, the biofuel production efficiency in harvesting and transporting large square bales makes them more cost competitive than the large round bale harvest system.
- In terms of trucking emissions, hauling energy sorghum to the biorefinery creates significantly more emissions than delivering switchgrass. The higher emission level is related to greater vehicle travel miles associated with energy sorghum deliveries caused by the larger feedstock draw area when compared to the vehicle miles to deliver switchgrass.
- Hauling switchgrass to the optimal site in west Tennessee using large round bale system produces the greater emissions, while the least emissions are generated from hauling large square bales to the optimal site in central Tennessee.
- Based on the estimated additional 1.2 million VMTs of feedstock transportation to the biorefinery in Robertson County, the emissions of NO_X, CO_2, PM_{10}, and $PM_{2.5}$ in eight feedstock supply counties increase by 0.12%, 0.04%, 0.15%, and 0.18%, respectively, when comparing with the overall baseline emissions.
- Combing the output of plant-gate cost and hauling emissions of feedstock, the biorefinery located in Springfield, Tennessee near the intersection of U.S. Highways 431 and 41 (about 25 miles north of Nashville, Tennessee, and 10 miles from the Kentucky border) is suggested to be the most preferred site to establish a switchgrass-based biorefinery.
- The total feedstock cost and emissions may change when the biorefinery can process multi-feedstock since the storage of feedstock will be lower if various LCB feedstocks can be harvested and hauled to the biorefinery in different periods throughout the year. Also, the capability of processing diverse LCB feedstocks may reduce feedstock draw area; hence lowering the transportation cost and hauling emissions.

INTRODUCTION

Establishing a commercially viable lignocellulosic biomass (LCB) biofuels industry is a major focus in the development of renewable energy in the United States (Osborne 2010). Provisions in federal legislation, such as the Energy Independence and Security Act of 2007 (U.S. Congress 2007) and the Food, Conservation, and Energy Act of 2008 (U.S. Congress 2008), have been enacted to accelerate the commercialization of advanced biofuels production, including biofuels generated from LCB feedstock. States have also created incentive programs to develop local bioenergy industries. Tennessee committed $70 million in 2007 to the Tennessee Biofuels Initiative to improve the economic feasibility of biofuel production from LCB (Goodman 2011). Starting in January 2010, Genera Energy LLC, a for profit company formed by The University of Tennessee under the 2007 initiative, partnered with DuPont Danisco Cellulosic Ethanol LLC to operate a demonstration biorefinery using corncobs and switchgrass as feedstocks in Vonore, Tennessee.

Given the success in the development of conversion technologies for LCB-based biofuels production at the demonstration biorefinery, a commercial-scale, switchgrass-based biorefinery to be placed in Tennessee by 2014 has been under discussion (Brass 2011). Establishment of a commercial-scale biorefinery is expected to increase truck traffic on road networks linking feedstock supply areas and the biorefinery. Two factors may influence the potential for increased truck traffic. First, switchgrass is expected to be grown primarily on lands that are currently in low biomass yielding pasture and hay activities that involve low levels of vehicle traffic in non-concentrated flow patterns (English et al. 2006). Second, switchgrass is capable of producing high yields on marginal lands commonly found in Tennessee but the density of harvested switchgrass in the field is low (Wright 2007). We estimate that a switchgrass-based biorefinery producing 50 million gallons of ethanol per year will need nearly 135 deliveries per day of large round bales by semi-truck. Thus, the transportation of switchgrass feedstock could potentially create social and environmental impacts on major roads and the communities around the biorefinery.

The social and environmental impacts of increased traffic induced by LCB feedstock shipments have been receiving greater attention in the literature (Gold and Seuring 2011). Kumar et al. (2006) applied economic, social, environmental, and technical criteria to rank alternatives for LCB feedstock transportation. They concluded that the projected increase in truck traffic is likely to increase public resistance if the plant is close to a community, and that rail transport reduces the number of loads and produces less emissions and congestion. Mahmudi and Flynn (2006) indicated that while rail shipment of LCB feedstock reduces emissions and congestion, it is not economical unless the shipping distance exceeds 120 miles. Thornley (2008) indicated that the proximity of conversion or preprocessing facilities to LCB feedstock is directly linked to transportation emissions. Nitrogen oxides (NO_x) emissions from harvesting and tractor operations in the field are also significant. According to the U.S. Environmental Protection Agency (EPA), highway vehicles currently are a major contributor to carbon monoxide (CO), NO_x, and volatile organic compounds (VOC) in the United States. Heavy duty trucks accounted for 50%, 56%, and 68% of NO_x, particulate matter (PM_{10}), and fine particle ($PM_{2.5}$) emissions, respectively, produced by all vehicles on highways in 2005 (U.S. EPA 2005).

Emissions from LCB feedstock transportation also have important implications in the life cycle assessment (LCA) of bioenergy produced from LCB feedstock. A full LCA analysis (i.e., a so-called *cradle to grave* analyses) is to “estimate potential environmental impacts (e.g. resource use and environmental consequences of releases) throughout a product’s life cycle from raw material production, use, end-of-life treatment and disposal” (U.S. EPA 2006). A full LCA analysis of switchgrass-based biofuels includes carbon emissions and other environmental indicators during five major stages: **1)** switchgrass production, harvesting and storage, **2)** switchgrass transportation between the field and biorefinery, **3)** switchgrass-to-biofuel conversion in the biorefinery, **4)** biofuel distribution, and **5)** biofuel utilization in fleets. Thus, understanding the emissions produced from hauling LCB feedstock to a biorefinery will be helpful to generate a more accurate LCA emission analysis.

Given the potential for developing a cellulosic biofuel industry in Tennessee, this study evaluates the emissions produced from LCB feedstock hauling to the optimal sites of a biorefinery in several regions of the state that have the least plant-gate cost of feedstock. Our specific research objectives are: **1)** to develop a comprehensive estimate of vehicle emissions caused by delivery of LCB feedstock to a commercial-scale biorefinery site, and **2)** to evaluate tradeoffs in plant gate feedstock costs and hauling emissions for alternative biorefinery locations in Tennessee. Plant-gate costs and hauling emissions were evaluated for large round and large square bale harvest, storage, and transportation systems. The results of this study have the potential to provide valuable information towards the development of a sustainable switchgrass-based biofuels industry in Tennessee and the southeastern United States.

APPROACH

The analysis of plant-gate costs of switchgrass feedstock and vehicle emissions to deliver the feedstock to the biorefinery was divided into two major steps. First, the least-cost feedstock draw area and location of the commercial-scale biorefinery was identified for each of three regions in Tennessee (eastern, central, and western) by minimizing feedstock plant-gate costs. The cost-minimization identified the most efficient road links within the feedstock draw area to the biorefinery based on the real road network for each region. Second, the existing traffic emissions on the road networks and the additional emissions produced from feedstock transportation were estimated and evaluated using the vehicle traffic flow data generated in the first step.

Two assumed capacities of the commercial-scale biorefinery, 50 and 75 million gallons of biofuel per year (MGY), were used to estimate the feedstock draw area. The biorefinery considered in this study was a single-feedstock conversion facility that would not process mixed feedstock. Plant-gate costs were evaluated for large round bale (LRB) and large square bale (LSB) harvest, storage, and transportation systems. The two systems are commonly used for the harvest and storage of hay and can also be used for switchgrass (Mooney et al. 2012). Switchgrass was the major feedstock examined in this study. In addition, the potential of energy sorghum to be a feedstock for the biofuel industry in Tennessee was explored. The potential feedstock supply area assumed in the analysis includes Tennessee and a buffer area within 50 miles adjoining the state border (see Figure 1). The three geographic (eastern, central and western) regions in Tennessee that were used in the analysis were defined by University of

Tennessee Extension (University of Tennessee 2012). The potential locations for the biorefineries was assumed to be limited to feasible industrial parks with access to water, power, and roads, as well as sufficient storage space in each region (see Figure 2).

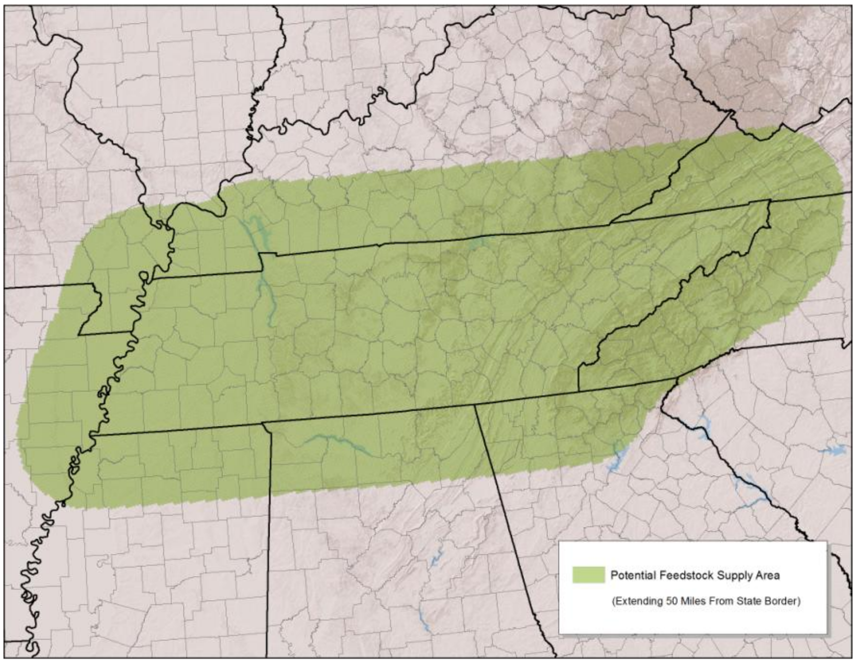

Figure 1. Potential feedstock supply area

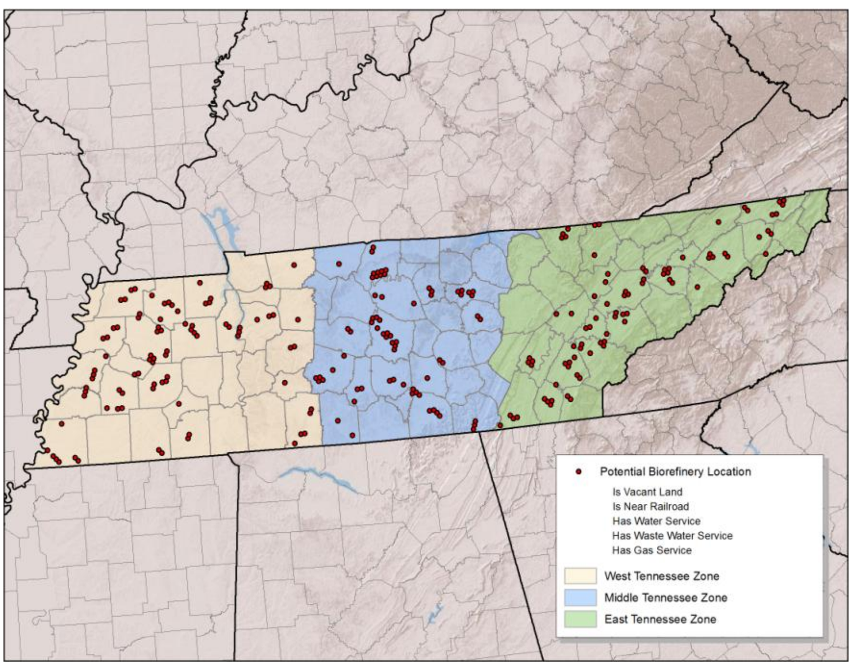

Figure 2. Potential industrial parks to site the biorefinery in the three Tennessee geographic regions used in the analysis

METHODS AND DATA

The methods and its data requirements used in estimating the minimized feedstock cost for the biorefinery location, feedstock delivery schedule and plant-gate cost are described. Based on the solution for biorefinery location and its delivery schedule, models used in determining vehicle emissions are discussed.

Determine Biorefinery Location, Feedstock Supply Area, and Delivery Schedule

A spatially-oriented, mixed-integer mathematical programming model, the Bio-Energy Site and Technology Assessment (BESTA), was employed to determine the location of the biorefinery, the feedstock draw area, and monthly feedstock delivery schedule for each bale type. The objective is to minimize plant-gate cost of production, harvest, storage, and transportation of switchgrass to the biorefinery, subject to constrains on feedstock production availability and the demand for feedstock by the biorefinery. The balance of monthly inventory and delivery of feedstock was maintained to assure sufficient feedstock supply for the biorefinery. In addition, dry matter losses during harvest, storage and transportation operations were incorporated into the cost minimization to balance the final delivery of feedstock and the demand of the biorefinery (Mooney et al., 2012). A complete description of the BESTA model is available in Gao (2011).

The BESTA model uses detailed spatial data from a GIS model, the Biofuels Facility Location Analysis Modeling Endeavor (BioFLAME) (Wilson 2009). The potential feedstock draw area was disaggregated into a vector database of contiguous 5 square-mile crop zones based on remote sensing data within the assumed feedstock supply regions. Federal lands in the region were excluded from the analysis. The crop zones are the geographic units used by BESTA to model areas in traditional agricultural production activities (e.g., barley, corn, cotton, hay, oats, pasture, soybean, sorghum, and wheat) and switchgrass feedstock production. To determine the potential area for LCB feedstock in each crop zone, a switchgrass price was determined by its production cost, or by its production cost plus net revenue from the next best production alternative (e.g., corn production), whichever is larger (Wilson 2009).

The street level network was applied to estimate transportation costs of switchgrass from the field to facility. The hauling distance from the field to the biorefinery was calculated as the distance between center point of the crop zone in which feedstock is produced and the center point of the crop zone where the biorefinery is located. A hierarchy, **1)** primary/major roads, **2)** secondary roads, **3)** local and rural roads, and **4)** other roads, based on the speed limits of each type of roads was used when generating the routes between points to locate the most accessible routes. Transportation costs include labor, operating, and ownership costs of tractors with front-end loaders used for loading and unloading of bales, and semi-trucks with trailers used for transporting bales from the field to the biorefinery. Cost for semi-trucks and trailers was calculated using estimated travel distances from the real street network in each region.

Nearly 658,000 dry tons (dt) of LCB feedstock per year were assumed to be required to maintain the year-round operation of a 50-MGY biorefinery based on a conversion rate of 76 gallons/dt of ethanol (Wang et al. 1999). Applying the same conversion rate, a 75-MGY biorefinery needs almost 987,000 dt of feedstock per year. The operations assumed in the supply chains of feedstock between the field and the biorefinery are: **1)** harvesting of feedstock in the field using mowing, raking, and baling operations; **2)** moving bales to edge of the field for either storage or loading and transport to the biorefinery; **3)** storing bales; **4)** loading bales for transport to the biorefinery; **5)** transporting bales to the biorefinery; and **6)** handling the bales at the plant. The biorefinery was assumed to be able to process both round and square bales.

It was assumed that feedstock is harvested once per year after a killing frost to minimize removable of nutrients with the harvest of biomass and to maximize biofuel yield. The large round bales and large square bales are then placed into storage at the edge of the field until transported to biorefinery. Storage protection was not applied to bales directly delivered after baling to the biorefinery during harvest season. The harvest costs consisted of machinery operating and ownership costs plus labor costs used for mowing, raking, baling, and loading. Storage costs included the materials (tarps and wooden pallets) used to protect those bales stored on the edge of field, and the labor and tractor costs for material handling and baling. The total storage cost for different bale types varied based on the treatments of top cover and surface protection methods. Dry matter losses for storage periods of up to 365 days for the large round and square bale systems were modeled using estimated losses by time in storage for switchgrass from Mooney et al. (2012). Labor costs plus operating and ownership costs for equipment and vehicles were obtained from Gao (2011) and Larson et al. (2010).

Traditional crop yields were from the SSURGO database at the sub-county level (U.S. Department of Agriculture, Natural Resources Conservation Service, 2012). Areas in each traditional crop for each crop zone were from the cropland layer database (U.S. Department of Agriculture, National Agricultural Statistics Service, 2011). Switchgrass and energy sorghum yields were from the POLYSYS model (English et al. 2006). The yield of mature switchgrass ranges between 8.0 and 9.4 dt/acre (see Figure 3), while the yield of mature energy sorghum after adjusting the lodging problem during harvest was estimated around 6.0−9.0 dt/acre (see Figure 4). The data for traditional crop prices used in the BESTA and BioFLAME models was for the 2010 crop year (U.S. Department of Agriculture, National Agricultural Statistics Service 2011). The budget information for traditional crops was from the Agricultural Policy Analysis Center’s Agricultural Budgeting System.

Minimizing the total plant gate costs of feedstock, BESTA identified the feedstock production area, location of the biorefinery, and monthly feedstock delivery schedule. By exporting this information to the BioFLAME model, the shortest path routes (favoring major roads) between the biorefinery and each supply area, along with the number of truckloads of feedstock being hauled along these routes, were generated. The BioFLAME model then extracted the individual links of road for each route and merged the information with the truck volume information. Truck traffic flows on the road system were used as the inputs for estimating the emissions produced by LCB feedstock transportation in the next step.

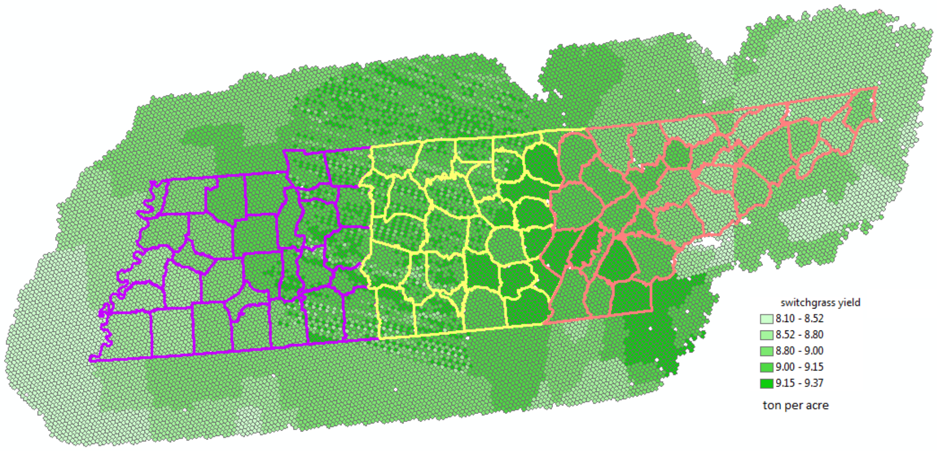

Figure 3. Potential yield of switchgrass used in this study

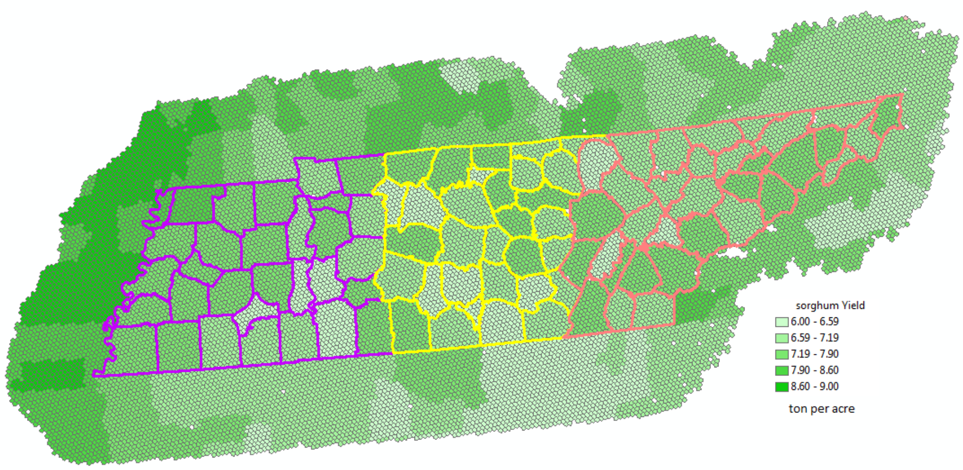

Figure 4. Potential yield of energy sorghum used in this study

Estimate the Existing and Additional Truck Emissions

In this study, the Motor Vehicle Emissions Simulator (MOVES), a computer program designed under the guidance of the U.S. Environmental Protection Agency (EPA), was used to estimate air pollution emissions from mobile sources. As of March 2, 2010, the US EPA approved the MOVES model (MOVES2010) for official use outside of California in state implementation plans (SIP) and air quality transportation conformity analysis as a replacement for MOBILE6.2 (U.S. EPA, 2010). Since the model allows customization to local areas and project level, this model can be used for various applications such as local air quality and transportation planning, assessment of emission impacts due to changes in vehicle speed, and local emission impacts of specific transportation projects. The version of the program that was used in this study is

MOVES2010a (hereafter referred to as MOVES). The methodologies and background information used for estimating emissions are discussed in the following sections.

Local emission inventories were created for each county in Tennessee and those counties of neighboring states that share a common physical border with the state. Annual emissions were aggregated at the county level to estimate the base case conditions that might exist in these counties before the introduction of truck traffic. Next, to simulate the effect of transporting feedstock from farms to the potential biorefinery site, emission rates were created in the form of look-up tables which could be applied to the various supply chains algorithms (referred to as the link case). The MOVES run specifications for these two situations are summarized in Table 1.

Table 1. Summary of the Run Specifications for MOVES Model

Detail Panel: Selections		**Base Case**	**Link Case**
Scale	**Domain/Scale**	National	Project
	Calculation Type	Inventory	Emission Rates
Time Spans	**Time Aggregation Level**	Hour	Hour
	Years	2010	2010
	Months	All months selected	Representative month selected (January, April, July & October)
	Days	Weekend & Weekdays	Weekdays
	Hours	All hours selected	11:00 - 11:59AM
Geographic Bounds	**Region**	County	Zone & Link
	States	Tennessee; all bordering states	Tennessee
	Counties	Specific counties selected for each state	Representative county selected (Blount, Cumberland, Davidson & Madison)
Vehicles/Equipment	**Fuels**	All selected	Diesel Fuel
	Source Use Types	All selected	Combination Short-haul Truck
Road Type	**Available Road Types**	All selected	Rural Restricted Access
Pollutant And Processes		NO_x; PM_{10} & $PM_{2.5}$; CO_2	NO_x; PM_{10} & $PM_{2.5}$; CO_2
		All processes selected	Running Exhaust only; Brakewear and Tirewear
General Output	**Output Database**	User supplied	User supplied
	Units	U.S Ton; Million BTU; Miles	Grams; Kilojoules; Miles
	Activity	All activities selected	Distance Traveled; Population
Output Emissions Detail	**Always**	Time(Month); Location (County); Pollutant	Time (Hour); Location (Link); Pollutant
	for All Vehicle/Equipment Categories	Fuel Type; Emission Process	Emission Process
	On Road/Off Road	Road Type; Source Use Type	Road Type
	Off Road	None	None

Base case

The National scale was selected, which uses a default database to allocate emissions to the individual counties based on a mix of national data and default allocation factors. Inventory was selected as the Calculation Type which provides emissions estimates on a mass per pollutant basis. The calendar year of evaluation was 2010. All months, days and hours were selected for the Time Spans, as well as Hour chosen for the Time Aggregation, which uses specific hourly input data (e.g., temperature, humidity, etc.) to calculate emissions for the time spans. For the Geographic Bounds, each county in Tennessee was selected in turn, as well as the border counties in neighboring states. All fuel types (e.g., diesel, gasoline, etc.), all source (or vehicle) types (e.g., passenger car, passenger truck, etc.), and all road types (e.g., rural restricted, rural unrestricted, etc.) were selected. The air pollutants that were modeled were oxides of nitrogen (NO_x), total primary PM_{10} and $PM_{2.5}$, and the equivalent CO_2. Total NO_x is the summation of nitrogen oxide (NO) and nitrogen dioxide (NO_2). Particulate matter less than 10 microns or less than 2.5-microns in aerodynamic diameter are PM_{10} or $PM_{2.5}$, respectively, which denote the size of the particles. Total PM refers to the summation of organic carbon, elemental carbon, and sulfate particulate derived from running exhaust, brake wear and tire wear. Primary particles refer to particles that are directly emitted into the air from the vehicles as compared to other particles that may be formed in the air from chemical change of gases (i.e., secondary particles).

Emissions for the equivalent carbon dioxide (CO_2) term incorporate all gasses that are emitted by the vehicle, which may have a global warming potential. All pollutant processes were selected and included running exhaust, crankcase start exhaust, and extended idling exhaust, etc. For the Output Database, the units were in U.S. tons of pollutant. Although activity output is not required for Inventory calculations, provided a quality control check of whether activity was properly entered in MOVES. Providing Output Emission Detail was useful because the results can be aggregated and analyzed later by the user.

A total of 95 counties were modeled for the state of Tennessee. In addition, a total of 188 border counties were modeled and included the counties of the following neighboring states: Alabama, Arkansas, Georgia, Illinois, Kentucky, Mississippi, Missouri, North and South Carolina, Virginia, and West Virginia. The output data were post-processed by summing all emissions per pollutant for each month, fuel type, emission process, and road type. Using Microsoft Excel, the results were aggregated using total emissions for each air pollutant in mass units of tons per year on a county basis.

Link case

The Project scale was selected, which permits the modeling of emission effects from individual roadway links that can be spatially connected to one another. However at the project level, specific data input details must be entered by the user because direct access by the model to the national default data is not allowed at this scale. The Emission Rate was selected as the Calculation Type and provides emissions estimates per unit of distance for running emissions. For the Time spans, again, the Time Aggregation level was Hour and the calendar year of evaluation was 2010. Each season of the year (i.e. spring, summer, fall, and winter) was modeled to reduce the computation time. A representative month of the year that best represented each season was selected (i.e. April, July, October, and January). In addition, only weekdays were modeled assuming deliveries typically occur Monday through Friday with the time between 11:00AM and 11:59AM used as the representative hour of trucking delivery.

For the Geographic Bounds it was necessary to select a single county to represent all the surrounding counties in the area because local meteorological data are required to run the model at the project link level. Thus, Blount, Cumberland, Davidson, and Madison counties in Tennessee were selected because a regional airport is located in each county and surface hourly temperature and humidity data for these counties are available from the National Climatic Data Center. Diesel fuel, combination short-haul truck, and rural restricted access were selected for Vehicles/Equipment fuel and Source Use Type and the Road Type, respectively. The air pollutants that were modeled were identical to those selected for the Base Case scenario, though only the Running Exhaust emission option was chosen for the NO_x Pollutant Processes. In addition, break wear and tire wear were selected for PM emissions. The emission units output were in grams of pollutant per mile (i.e., distance of travel) because selecting tons in the output for the link cases may produce emissions of zero if emissions are less than one ton (possible due to rounding). Finally, the Output Emission Details were Emission Process by Road Type.

The MOVES model provides a graphical user interphase called the County Data Manager (CDM) that facilitates the input of local data, which is required by the model when the domain/scale is set to the project level. The objective was to create a look-up table of emission rates using a generic roadway links file. This file was created by combining the following parameters in a factorial type design: the link length was 10 miles; the link volume was for one vehicle; the range of average vehicle speeds along the link was 10 to 70 miles per hour (mph) at increments of 10 mph; the range of average road grades was -8% to +8% at increments of 0.5%. The link Source Type, as previously mentioned, was the Combination Short-haul Truck. The Age Distribution for the Source Type was taken from the national default age distributions.

The data of Fuel Supply, Fuel Formulation, and Fuel Subtype for conventional diesel fuel were taken from the national default database. In order to extract this data, the fuel supply, formulation, and subtype tables were exported using the MySQL database tool that came preinstalled with MOVES. It should be noted that the fuel supply/formulation for January and April are identical as well as the fuel supply/formulation for July and October. These are often discussed as winter and summer fuel formulations and currently only reflect differing sulfur content. The local meteorological data of temperature and relative humidity were also imported into MOVES using the CDM for the season (month), county (zone), and hour.

A total of 16 separate modeling runs were performed at the project scale level. Four runs each (i.e., per season) for the four representative counties. The output data were post-processed by aggregating the emission rate per distance for each air pollutant. The results were aggregated into a Microsoft Excel file that contained emission rates for each air pollutant in units of grams per mile for a link length of 0.1 mile, through the range of link average speeds at increments of 10 mph and the range of road grades at increments of 0.5% on a county basis (i.e., 95 counties total) for each of the four seasons.

Sensitivity analyses on emission rates and grades

To illustrate how spatial attributes may affect the estimates of truck emissions in MOVES model, a sensitivity analysis was conducted to examine the variations in emission estimates related to road grades. Emission rates were simulated using a 10-minute driving episode at constant vehicle speeds ranging from 10 mph to 70 mph in a 10 mph increment using road grades that ranging from –6% to 6% in 0.5% increments. The emission rates were for diesel fueled combination long-haul trucks with 2005 model year and three years old. Figure 5 shows NO_X and $PM_{2.5}$

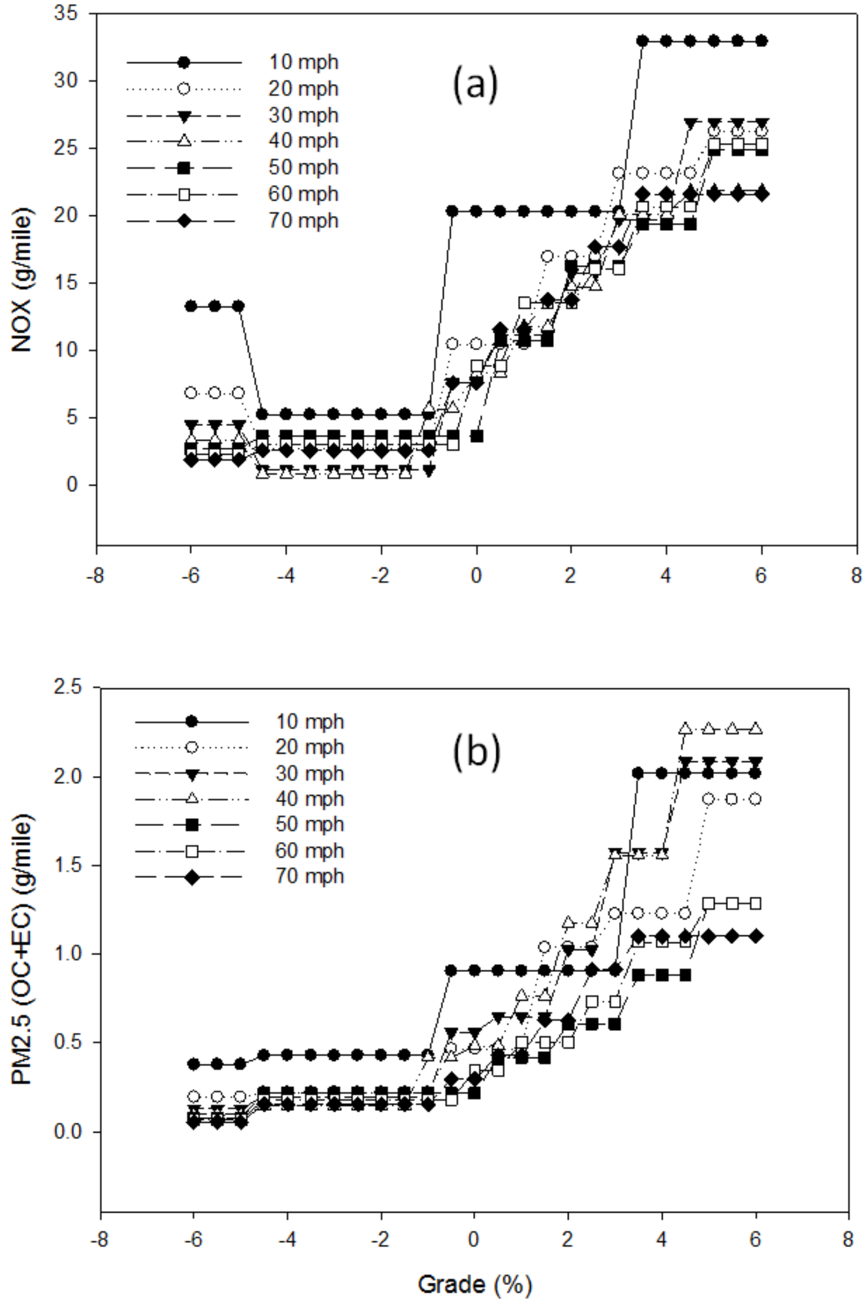

Figure 5. NO_x and $PM_{2.5}$ emission rates by grade and speed: (a) NO_x and (b) $PM_{2.5}$ (CO+EC)

(EC+OC) exhaust emission rates for each speed and grade. As shown, lowest constant speed (10 mph) generated the highest NO_X emissions overall. At positive road grades, both emission rates were progressively higher as road grade increased, but once more, highest emissions were not generated by the highest speed (70 mph). At negative road grades, both emission rates were not changed dramatically compared to positive road grades. Between -1% and -4.5% grades, the NO_X emissions rates were the similar for different constant speeds. At higher negative grades between -4.5% and -6%, the NO_X emission rates increased when compared to the emission rates between -1% and -4.5% grades. On the other hand, $PM_{2.5}$ (EC+OC) emission rates decreased as road grades decreased from -4.5% to -5%. In this study, emission rates were obtained for various road grades with various average speeds. Therefore, emissions that were calculated based on emission rates for different road grades resulted in different emission levels even with the same average speed.

RESULTS AND DISCUSSION

The plant-gate cost of feedstock, optimal location of biorefinery, monthly deliveries of feedstock under the two harvesting/storage/transportation systems (LRB and LSB) for switchgrass are presented first, followed by the output of the truck emissions of the base case and the link case, respectively. Likewise, similar analyses associated with energy sorghum are also discussed in this section.

Switchgrass-based Biorefinery

Capacity of 50 million gallons per year (MGY)

Table 2 summarizes the optimal plant-gate costs of switchgrass for a biorefinery with an annual capacity of 50 MGY for both large round bale (LRB) and large square bale (LSB) systems by region. The least-cost LRB storage system was switchgrass stored on the ground without a tarp. Consistent with the partial budgeting results by Mooney et al. (2012), the value of the dry matter preserved using tarps and pallets for protection was not large enough to offset the costs of protection with the LRB system. By comparison, the optimal storage strategy for the LSB system is to use tarps and pallets because storage DML was higher.

For the LRB system, the estimated total plant-gate cost for delivering about 658,000 tons of round bales to the least-cost site in each of the three regions ranged between $47.1 million ($72/dt) and $48.4 million ($74/dt). Harvest costs associated with round bales accounted for more than half of the total plant gate cost, whereas transportation costs were estimated at about 25% of total cost in the LRB system. Total plant-gate feedstock costs under the LSB system for the 50-MGY biorefinery were less than that in the LRB system, even though storage costs were incurred in the LSB system but not the LRB system. The LSB system has the cost advantage of $3 to $4 per dt when comparing to the LRB system, which is primarily due to lower harvest and transportation costs. These cost efficiencies more than offset the larger storage DML with the LSB system. The least-cost biorefinery location in central Tennessee region was found to be the most economic efficient location among the three regions in the Tennessee regions.

Table 2. Plant-gate Cost of Switchgrass for a 50-MGY Biorefinery

	LRB*						LSB*					
	East		Central		West		East		Central		West	
Storage option (top/bottom)	untarp/ground						tarp/wood pallet					
Total Feedstock Cost (million $)	$	48.2	$	47.1	$	48.4	$	46.3	$	45.4	$	46.4
Production	$	9.3	$	9.1	$	9.0	$	9.2	$	9.3	$	9.2
Harvest	$	27.0	$	26.6	$	26.5	$	23.9	$	23.9	$	23.9
Storage	$	-	$	-	$	-	$	3.3	$	3.3	$	3.3
Transportation	$	11.9	$	11.4	$	12.9	$	9.9	$	8.8	$	10.0
Feedstock Cost/dt	$	73	$	72	$	74	$	70	$	69	$	70
Biorefinery Location	Greene		Robertson		Lawrence		McMinn		Robertson		Lawrence	
Total Harvested Area	80,673		78,038		77,699		79,715		80,061		79,680	

*LRB: large round bale system, LSB: large square bale system

The feedstock draw area and biorefinery location in each region under LRB and LSB systems are illustrated in Figures 6 and 7, respectively. For the LRB system (Figure 6), the feedstock draw area covered a seven county area in the east Tennessee region. By contrast, the projected feedstock draw area for the biorefinery location in west Tennessee covered 11 counties. Hay is the dominate crop planted in east Tennessee but is less prevalent in west Tennessee, which has a much higher proportion of its agricultural lands in grains, oilseeds, and cotton. Given that the opportunity cost of converting hay land to switchgrass production is the least among all crops, a more compact feedstock draw area (number of counties involved) was observed at the east Tennessee site. However, the total switchgrass acreage in the feedstock draw area at the west Tennessee site was less than the acreage at the east Tennessee site (see Table 2), and is influenced by the yield of switchgrass in each region. Switchgrass yields in the draw area at the optimal site of the biorefinery in Greene County in northeast Tennessee are lower relative to the yields in the draw areas of the optimal biorefinery locations in west and central Tennessee (see Figure 3). Thus, a larger harvested switchgrass area was required in the seven county draw area for the east Tennessee site.

Harvested switchgrass acreage in the draw areas for the LSB system was higher than the acreages for the LRB system for the optimal biorefinery sites in west and central Tennessee (see Figure 7 and Table 1). The larger harvested area was required because square bales had higher storage DML than round bales. However, the harvested acreage in the draw area was similar in each of the three regions under the LSB system (~80,000 acres). The optimal biorefinery site was the same for the LRB and LSB systems for the central and west Tennessee regions, while the model relocated the optimal location of biorefinery from Greene County to McMinn County in the east Tennessee region, likely due to the yield difference. The harvested area for the biorefinery located in McMinn County using LSB system was about 1,000 acres less than that for the site located in Greene County employing LRB system; however, the draw area in the latter case was much larger than the former one due to the difference in availability of the relatively cheaper hay land.

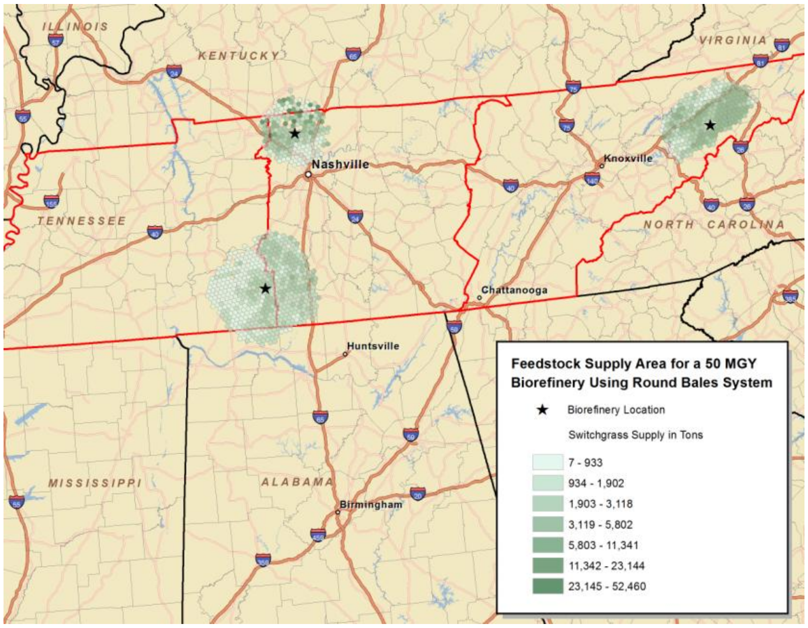

Figure 6. Switchgrass supply area for a 50-MGY biorefinery using round bales

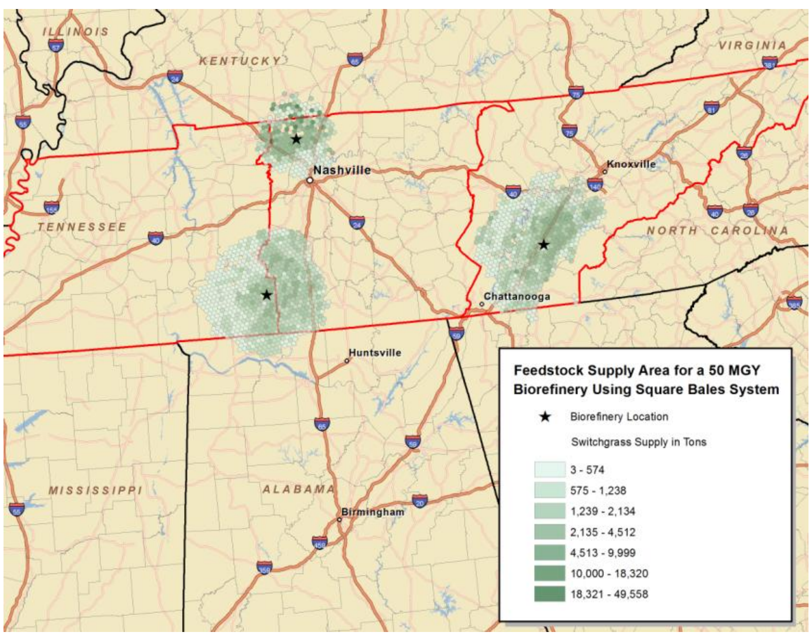

Figure 7. Switchgrass supply area for a 50-MGY biorefinery using square bales

Among all three regions, the biorefinery with the most economic feedstock cost was positioned in Springfield, TN near the intersection of U.S. Highways 431 and 41 (about 25 miles north of Nashville, TN, and 10 miles from the Kentucky border). For all of the sites, the feedstock was supplied by land located within 50 miles of the biorefinery, thus making trucking the most efficient mode. Monthly deliveries of switchgrass on the road networks were identified for each of the biorefineries with the optimal feedstock cost by region.

As an example to illustrate the emission analysis, the emissions of the base case (existing all vehicle traffics) and the link case (additional truck traffics of switchgrass) for the optimal site of biorefinery using square bales in central Tennessee are presented in Table 3. The overall increase of vehicle miles traveled (VMT) from the additional truck traffic is also included in Table 3. Total VMTs from truck flows of feedstock transportation were more than 1.2 million miles for all 8 counties in one year (three in Kentucky and five in Tennessee). The estimated baseline level of NO_x, CO_2, PM_{10}, and $PM_{2.5}$ emissions from all vehicles in those eight counties in 2010 were nearly 26,300 tons, 8,100,000 tons, 1,230 tons and 900 tons, respectively. After adding the annual truck traffic of switchgrass shipment to the biorefinery in Robertson County, the emissions of NO_x, CO_2, PM_{10}, and $PM_{2.5}$ in the study area increased by 0.12%, 0.04%, 0.15%, and 0.18%, respectively, when comparing the overall emissions produced by existing overall traffics in the base case. In this supply chain system, increased truck traffics in Robertson County accounted for nearly 80% of total VMT. Similarly, the highest increase in emissions (both in level and growth rate) was also seen in Robertson County where NO_x, PM_{10}, and $PM_{2.5}$ emissions increased by 0.97%, 1.52%, and 1.65%, respectively.

The additional CO_2 emission resulting from switchgrass deliveries to the biorefinery in Robertson County, TN, under LSB system is mapped in Figure 8. As expected, the additional emissions in those feedstock crop zones were modest. However, the emissions on the major roads, the most efficient links, increased substantially. Also, the amount of emissions produced on these links was clearly related to the density of feedstock supply by each crop zone. For the additional 1.2 million VMTs for feedstock transportation on the road system in related counties, it was estimated that the CO_2 emission increased by almost 1.7 milligrams (Mg) per month on links connecting to the entrance of the biorefinery. The similar pattern was also found in other emissions, such as NO_x, PM_{10}, and $PM_{2.5}$. Applying the same procedure, increased CO_2 emissions from hauling switchgrass to the biorefinery at the optimal site in the east and west regions were depicted in Figures 9 and 10, respectively.

To provide a better picture of the regional emission impact of feedstock transportation, Table 4 summarizes the emissions in the base case and the link case under the two supply chain systems for the optimal biorefinery site in each region. Because of the Appalachian Mountains, the average slope of the roads in the east (3.79 in Greene County and 3.11 in McMinn County) was higher than the road slope in the central and west regions (<3.00). Switchgrass hauling to the optimal site in west Tennessee using LRB system generated the highest VMTs (more than 2.2 million miles), while the least VMTs (about 1.2 million miles) were produced from feedstock deliveries to the biorefinery in Robertson County using the LSB supply chain system. Given the least miles traveled by those trucks and the flatter gradient of road networks in central Tennessee, the biorefinery in Robertson County generated the least emissions under both systems in levels and percentage when comparing to the optimal sites in the other two regions. In contrast, the significant travel miles by switchgrass trucking in the west region produced the most emissions to produce biofuel using the same capacity of biorefinery.

Table 3. Estimated Emissions in the Base Case and Link Case from Switchgrass Hauling in Central Tennessee

	Average	Baseline emissions in tons/year				Additional VMT in miles/year & emissions in tons/year					% increase			
Bledsoe	**Slope**	**NO_x**	**CO_2**	**PM_{10}**	**$PM_{2.5}$**	**VMT**	**NO_x**	**CO_2**	**PM_{10}**	**$PM_{2.5}$**	**NO_x**	**CO_2**	**PM_{10}**	**$PM_{2.5}$**
Logan, KY	2.07	623.3	180,950.4	26.5	19.8	132,112.3	3.0	343.5	0.2	0.2	0.48	0.19	0.69	0.83
Simpson, KY	2.07	991.8	205,099.4	34.3	29.5	18,132.5	0.5	48.4	0.0	0.0	0.05	0.02	0.08	0.08
Todd, KY	0.89	308.5	85,890.5	12.3	9.6	9,232.5	0.2	22.9	0.0	0.0	0.07	0.03	0.10	0.12
Cheatham, TN	2.74	1,109.7	267,321.1	41.3	34.8	28,059.2	0.7	80.6	0.0	0.0	0.06	0.03	0.11	0.12
Davidson, TN	2.44	15,167.8	5,012,014.4	755.0	530.5	15,305.2	0.4	41.8	0.0	0.0	0.00	0.00	0.00	0.00
Montgomery, TN	2.71	2,681.2	817,904.0	123.1	87.4	22,081.3	0.6	63.9	0.0	0.0	0.02	0.01	0.03	0.04
Robertson, TN	2.46	2,495.7	607,940.5	96.1	79.2	978,529.3	24.3	2,623.2	1.5	1.3	0.97	0.43	1.52	1.65
Sumner, TN	2.72	2,878.7	893,149.9	134.7	98.0	27,657.8	0.7	79.0	0.0	0.0	0.02	0.01	0.03	0.04
Total	**2.26**	**26,256.7**	**8,070,270.1**	**1,223.3**	**888.8**	**1,231,110.2**	**30.3**	**3,303.4**	**1.8**	**1.6**	**0.12**	**0.04**	**0.15**	**0.18**

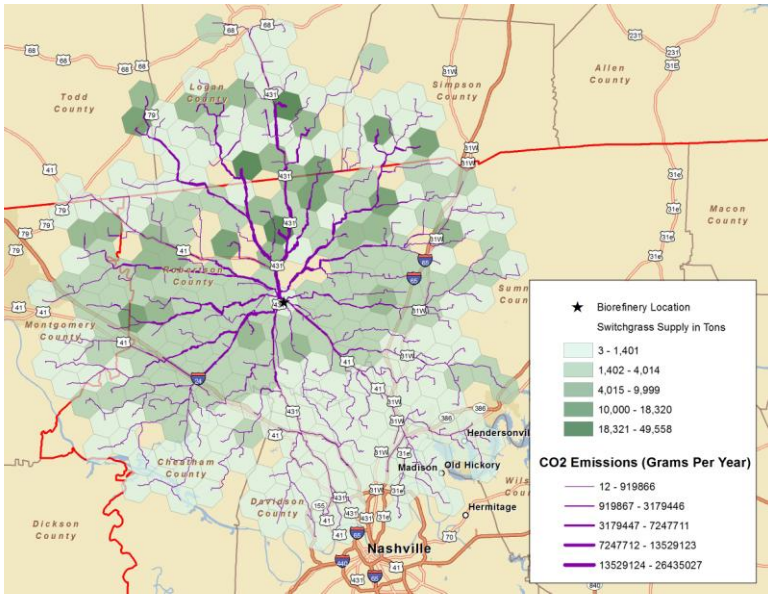

Figure 8. Annual CO_2 emissions produced from hauling switchgrass square bales to a 50-MGY biorefinery in central Tennessee

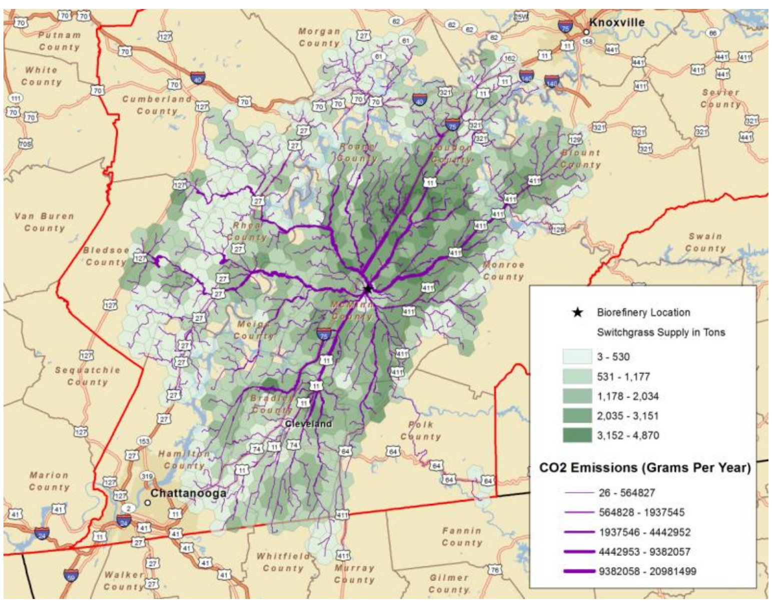

Figure 9. Annual CO_2 emissions produced from hauling switchgrass square bales to a 50-MGY biorefinery in east Tennessee

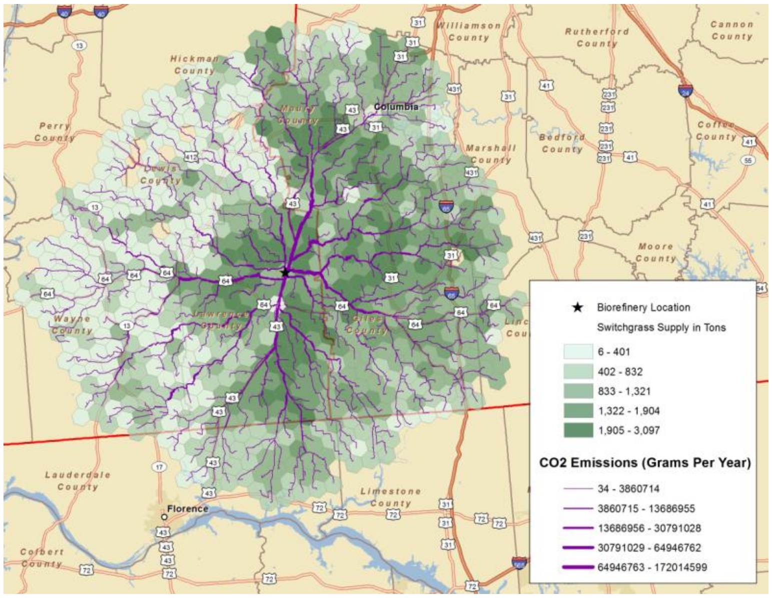

Figure 10. Annual CO_2 emissions produced from hauling switchgrass square bales to a 50-MGY biorefinery in west Tennessee

Table 4. Trucking Emissions from Hauling Switchgrass to a 50-MGY Biorefinery by Supply Chain System and Region in Tennessee

	LRB*			LSB*		
	East	Central	West	East	Central	West
Biorefinery location	Greene	Robertson	Lawrence	McMinn	Robertson	Lawrence
# of counties related	7	8	11	17	8	11
Average road slope	3.79	2.42	2.93	3.11	2.26	2.64
VMTs (miles)	1,477,878	1,431,231	2,259,666	1,932,794	1,231,110	1,968,441
Base case (tons)						
NO_x	15,527	26,257	11,899	39,036	26,257	11,899
CO_2	4,207,035	8,070,270	3,139,225	11,073,869	8,070,270	3,139,225
PM_{10}	657	1,223	480	1,676	1,223	480
$PM_{2.5}$	507	889	375	1,257	889	375
Link case (tons)						
NO_x	38.8	35.7	56.7	48.2	30.3	49.4
CO_2	4,379.7	3,899.3	6,221.5	5,268.1	3,303.4	5,432.5
PM_{10}	2.5	2.2	3.5	2.9	1.8	3.1
$PM_{2.5}$	2.2	2.0	3.2	2.6	1.6	2.8
Emission increase (%)						
NO_x	0.25	0.14	0.48	0.12	0.12	0.42
CO_2	0.10	0.05	0.20	0.05	0.04	0.17
PM_{10}	0.38	0.18	0.74	0.18	0.15	0.65
$PM_{2.5}$	0.44	0.22	0.84	0.21	0.18	0.74

*LRB: large round bale system, LSB: large square bale system

Combining the economic and environmental indicators of each site by bale system can help identify the optimal biorefinery location that satisfies the development of a sustainable biofuel industry. Figure 11 presents both plant-gate costs and CO_2 emissions of hauling switchgrass feedstock to a potential 50-MGY biorefinery using alternative supply chain systems in different regions. Given that the biorefinery capacity are identical, the total feedstock cost of the LRB supply chain system was about $2 million (or 4%) higher than the LSB system; however, the bigger draw area of the LSB system creates higher VMTs, and subsequently more trucking emissions. For the biorefinery in the optimal location of central and west Tennessee, the LSB system outperformed the LRB system in both feedstock plant-gate cost and CO_2 emissions. Among all potential supply chain systems and optimal locations in each region, the 50-MGY biorefinery located in central Tennessee (Robertson County) was found to be the most sustainable with the least economic costs and feedstock transportation emissions.

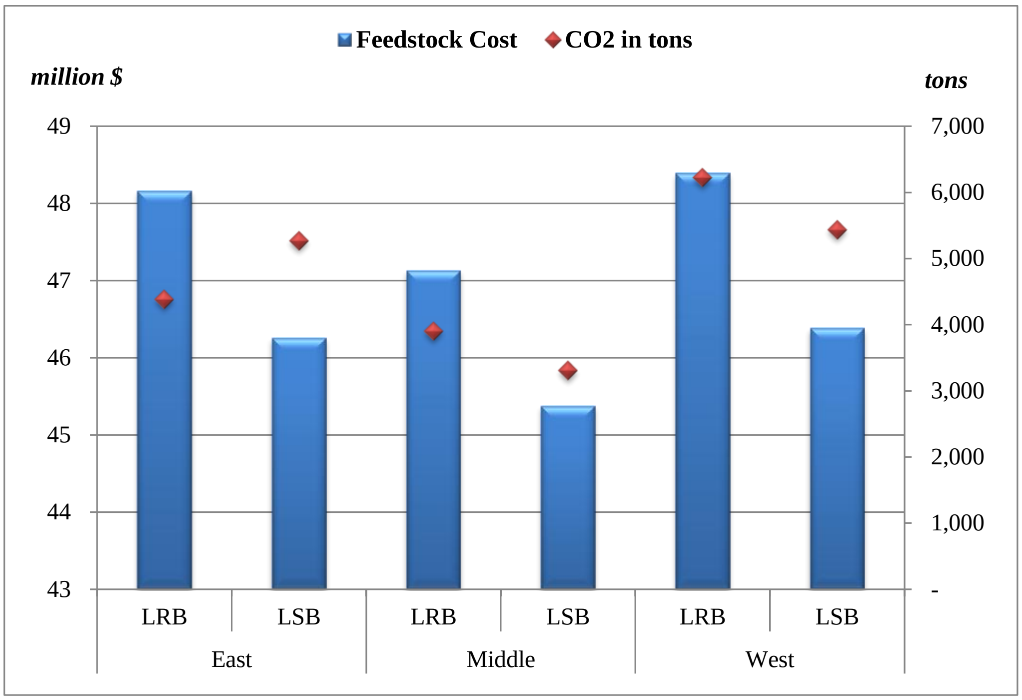

Figure 11. Total plant-gate costs and hauling emissions (CO_2) of switchgrass to a 50-MGY biorefinery using alternative supply chain systems by region in Tennessee

Capacity of 75 million gallons per year (MGY)

Table 5 summarizes plant-gate cost of switchgrass to a 75 MGY capacity biorefinery using the LRB and LSB harvesting/storage/transportation systems in three regions of Tennessee. With a larger capacity biorefinery the demand for feedstock increased the harvested area of feedstock by system in each region, which ranged between 116,750 and 121,005 acres among six evaluated cases. The total feedstock plant-gate costs for supplying nearly 987,000 tons of switchgrass ranged between $68.8 million and $74.2 million. The feedstock plant-gate costs of supplying round bales to the biorefinery at the optimal site in west Tennessee was the highest ($75/dt),

Table 5. Plant-gate Cost of Switchgrass for a 75-MGY Biorefinery

	LRB*			LSB*		
	East	Central	West	East	Central	West
Storage option (top/bottom)	untarp/ground			tarp/wood pallet		
Total Feedstock Cost (million $)	$ 74.1	$ 71.5	$ 74.2	$ 71.2	$ 68.8	$ 70.9
Production	$ 13.9	$ 13.6	$ 13.5	$ 13.9	$ 14.0	$ 13.8
Harvest	$ 40.4	$ 39.9	$ 39.8	$ 35.9	$ 35.9	$ 35.9
Storage	$ -	$ -	$ -	$ 5.0	$ 5.0	$ 5.0
Transportation	$ 19.7	$ 18.0	$ 20.9	$ 16.5	$ 13.8	$ 16.3
Feedstock Cost/dt	$ 75	$ 72	$ 75	$ 72	$ 70	$ 72
Biorefinery Location	Greene	Robertson	Lawrence	McMinn	Robertson	Lawrence
Total Harvested Area	121,005	117,303	116,758	119,842	120,301	119,759

*LRB: large round bale system, LSB: large square bale system

while the biorefinery in the central Tennessee using square bale system received the lowest plant-gate cost ($70/dt). Again, feedstock costs under LSB system were lower than that using LRB system. Compared to the cost for the 50-MGY biorefinery, the transportation cost increased the most (as high as 68%) among all cost components since the draw area of feedstock increased significantly. Similar to the case of 50-MGY biorefinery, the biorefinery sited in central Tennessee using square bales of switchgrass got the most economical feedstock cost.

The feedstock draw area and location of biorefinery in each region using LRB and LSB systems are mapped in Figures 12 and 13, respectively. The optimal location of the 75-MGY biorefinery in each region in both systems was very similar to that for the 50-MGY biorefinery. For the LRB system (Figure 12), the feedstock draw area for the biorefinery in east, central and west Tennessee covered 15, 8 and 14 counties, respectively. The difference in the size of feedstock draw area by region was related to the feedstock supply density of each crop zone. Some crop zones in central Tennessee provided significantly higher amount of switchgrass (e.g. nearly 77,000 tons per crop zone annually) compared to other crop zones in the east and west regions so that the counties needed to supply switchgrass for the central site were less. Similar situation was also observed in the LSB system (see Figure 13).

A summary of the emissions in the base case and the link case associated with LRB and LSB systems for the optimal site by region is presented in Table 6. Since the draw area of feedstock in central Tennessee was concentrated in a fewer counties than the related counties in the other two regions, the VMTs of switchgrass hauling to the biorefinery in Robertson County were smaller. In addition, the average road grade in related counties in central Tennessee was also lower than road grades in east and west Tennessee, causing emissions in the link case of the biorefinery in the Robertson County to be less. Since square bales have the advantage of transportation efficiency, the biorefinery sited in central Tennessee using large square bales produced less feedstock transportation emissions. Total estimated emissions produced from hauling switchgrass round bales to the biorefinery in Lawrence County in west Tennessee was the highest among the six cases given the total VMTs of 4.2 million miles. The emissions of NO_x, CO_2, PM_{10}, and $PM_{2.5}$ increased by 0.51%, 0.20%, 0.75% and 0.90%, respectively, when comparing with the overall emission in the base case.

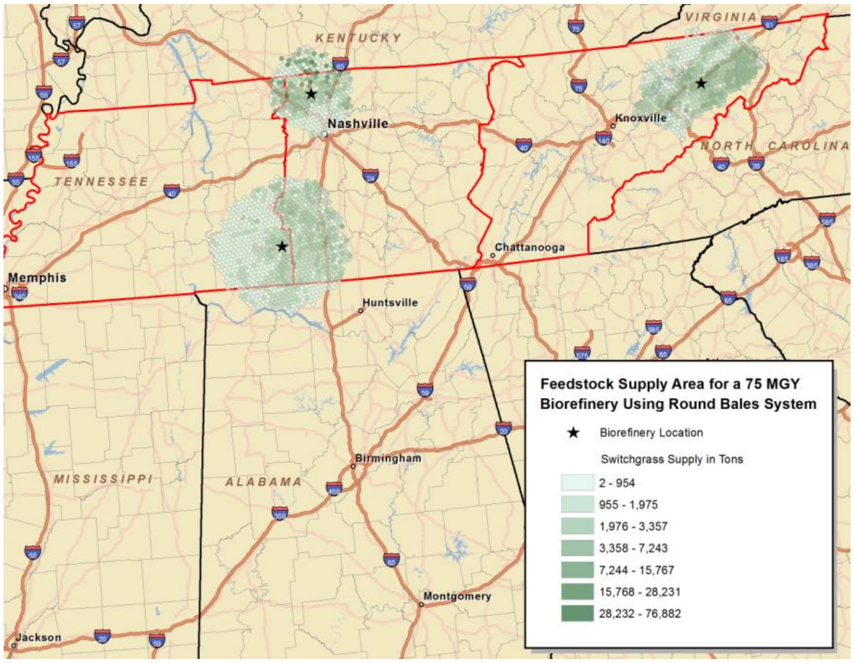

Figure 12. Switchgrass supply area for a 75-MGY biorefinery using round bales

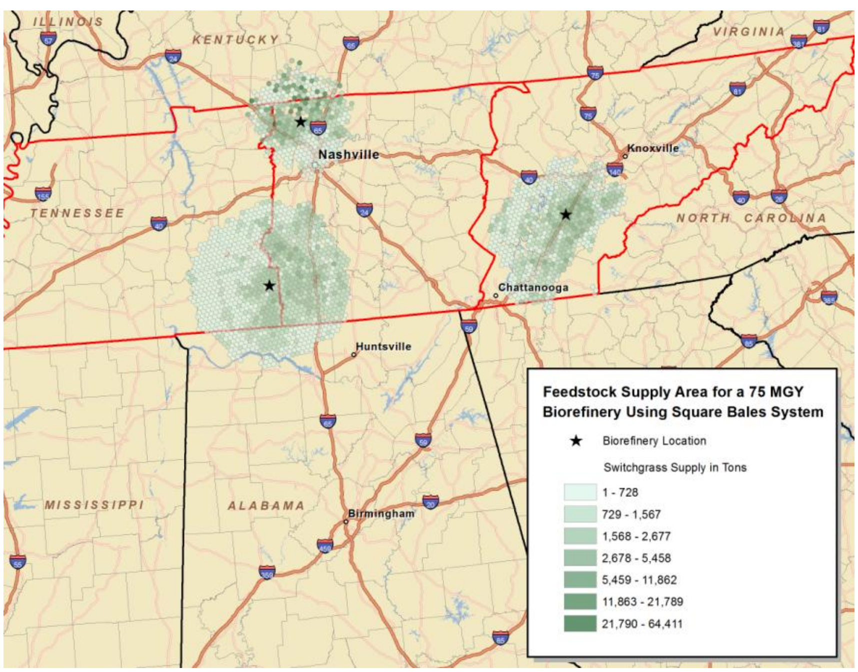

Figure 13. Switchgrass supply area for a 75-MGY biorefinery using square bales

Table 6. Trucking Emissions from Hauling Switchgrass to a 75-MGY Biorefinery by Supply Chain System and Region in Tennessee

	LRB*			LSB*		
	East	Central	West	East	Central	West
Biorefinery location	Greene	Robertson	Lawrence	McMinn	Robertson	Lawrence
# of counties related	15	8	14	27	10	18
Average road slope	4.15	2.22	2.46	3.31	2.29	2.50
VMTs (miles)	3,627,487	2,584,141	4,210,082	3,925,696	2,300,679	3,673,412
Base case (tons)						
NO_x	30,131	26,257	20,616	49,560	30,308	23,629
CO_2	8,559,944	8,070,270	5,784,043	13,769,875	9,163,984	6,670,011
PM_{10}	1,310	1,223	875	2,093	1,391	1,004
$PM_{2.5}$	984	889	657	1,593	1,021	752
Link case (tons)						
NO_x	96.8	63.2	105.9	97.6	56.1	92.4
CO_2	10,681.0	6,876.1	11,614.2	10,712.1	6,109.9	10,155.3
PM_{10}	6.1	3.8	6.6	5.9	3.4	5.8
$PM_{2.5}$	5.5	3.4	5.9	5.3	3.0	5.2
Emission increase (%)						
NO_x	0.32	0.24	0.51	0.20	0.19	0.39
CO_2	0.12	0.09	0.20	0.08	0.07	0.15
PM_{10}	0.47	0.31	0.75	0.28	0.24	0.57
$PM_{2.5}$	0.55	0.38	0.90	0.33	0.30	0.69

*LRB: large round bale system, LSB: large square bale system

Combining the output of plant-gate cost and vehicle emissions of feedstock hauling to the biorefinery by region in Figure 14, the preferred site for investing a 75-MGY switchgrass-based biorefinery in Tennessee was found to be in Robertson County in central Tennessee. Comparing the two feedstock harvest/storage/transportation systems, large square bales again showed the advantage in both feedstock cost and emissions of feedstock hauling over the large round bale system, primarily driven by the transportation efficiency of large square bales.

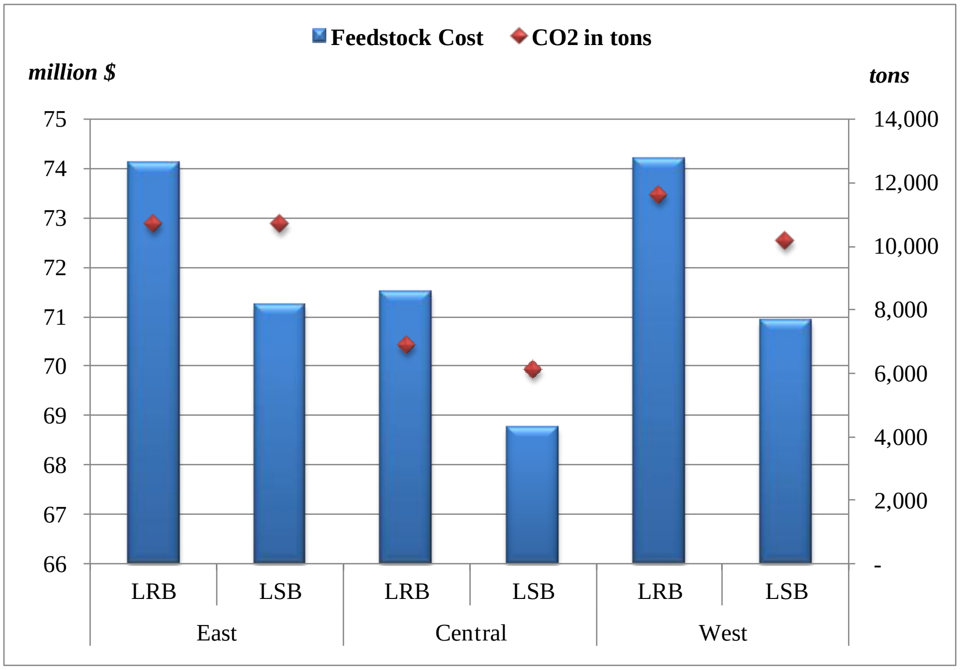

Figure 14. Total plant-gate costs and hauling emissions (CO_2) of switchgrass to a 75-MGY biorefinery using alternative supply chain systems by region in Tennessee

Energy Sorghum-based Biorefinery

Capacity of 50 million gallons per year (MGY)

The least plant-gate costs by feedstock supply chain systems for a 50-MGY energy sorghum feedstock biorefinery for three regions of Tennessee are presented in Table 7. In contrast to switchgrass, the least-cost storage exercise in the LRB system was to store energy sorghum on the ground *with a tarp*. The output suggests that dry matter saved using tarps for protection outweighed the costs of protection under LRB system. The cost of producing additional tonnages due to dry matter losses was significant since energy sorghum is an annual crop needing more inputs for its production than a perennial grass. The optimal storage option for the LSB system was to use both tarps and pallets to handle the high DML.

Compared to the plant-gate cost of switchgrass, energy sorghum is an expensive feedstock to produce in Tennessee. In the LRB system, the total plant-gate costs of 658,000 tons of energy sorghum ranged between $71.9 million and $97.8 million among the three regions, about 48% to 103% higher than the cost of switchgrass under the same system and region. The feedstock cost and harvested area in east Tennessee were the highest due to relatively lower yields of energy sorghum around the site of biorefinery in Hamilton County (see Figure 4). In addition, the transportation cost of hauling energy sorghum to the biorefinery in east Tennessee was higher than for the sites in the central and west regions due to larger draw area of energy sorghum in east Tennessee. The total feedstock costs for the biorefinery in central and west Tennessee were similar (about $71 million for total or $110 per dry ton). Generally, the feedstock cost in LSB system was slightly lower than that of LRB systems.

Table 7. Plant-gate Cost of Energy Sorghum for a 50-MGY Biorefinery

	LRB*			LSB*		
	East	Central	West	East	Central	West
Storage option (top/bottom)	tarp/ground			tarp/wood pallet		
Total Feedstock Cost (million $)	$ 97.8	$ 72.1	$ 71.9	$ 97.5	$ 71.0	$ 69.9
Production	$ 47.3	$ 30.5	$ 28.0	$ 50.8	$ 32.3	$ 29.5
Harvest	$ 29.5	$ 27.1	$ 26.1	$ 28.3	$ 25.5	$ 24.3
Storage	$ 1.8	$ 1.8	$ 1.8	$ 3.3	$ 3.3	$ 3.3
Transportation	$ 19.0	$ 12.7	$ 16.0	$ 15.0	$ 9.9	$ 12.8
Feedstock Cost/dt	$ 149	$ 110	$ 109	$ 148	$ 108	$ 106
Biorefinery Location	Hamilton	Robertson	Obion	Hamilton	Robertson	Obion
Total Harvested Area	102,228	85,311	78,396	108,613	90,454	82,666

* LRB: large round bale system; LSB: large square bale system

Figures 15 and 16 depict feedstock draw area and location for a 50-MGY biorefinery with the least plant-gate cost of energy sorghum by region in Tennessee using LRB and LSB systems, respectively. Clearly depicted is the feedstock draw associated with the biorefinery in east Tennessee area was much larger than the central and west regions. Since it is assumed that energy sorghum could only be planted on crop land, lack of available crop land in east Tennessee resulted in the model to search a larger area to produce energy sorghum. Also, the feedstock draw area for the biorefinery in east Tennessee reached the boundary of the 50-mile buffer in Georgia and Alabama (see Figure 1), suggesting the difficulty of acquiring crop land in this region. In addition, the density of feedstock supply in each crop zone in the east region was smaller—less than 1,000 tons per year. In contrast, available crop land and yields of energy sorghum in central and west Tennessee were higher, thus generating higher feedstock supply density in crop zones.

The optimal location of the biorefinery in all three regions, regardless of feedstock supply chain systems, was close to the state's border, primarily driven by the yield of energy sorghum in crop zones. For example, the crop zones supporting the biorefinery located in Obion County in west Tennessee were mainly located in southwest Kentucky and southeast Missouri where yields are higher compared to crop zones in central and west Tennessee (see Figure 4). Similarly, the model suggests that south-central Kentucky was the major area supplying energy sorghum to the biorefinery in Robertson County due to higher yields. For the biorefinery in Hamilton County in east Tennessee, the feedstock draw area covered up to total 36 counties in Tennessee, Georgia and Alabama. Since it was assumed that the biorefinery can only be located within Tennessee, the model located the biorefinery close to the state's border to acquire the feedstock produced in neighboring states implying less-expensive energy sorghum availability if the biorefinery was located in the surround states of Kentucky, Missouri, or Alabama.

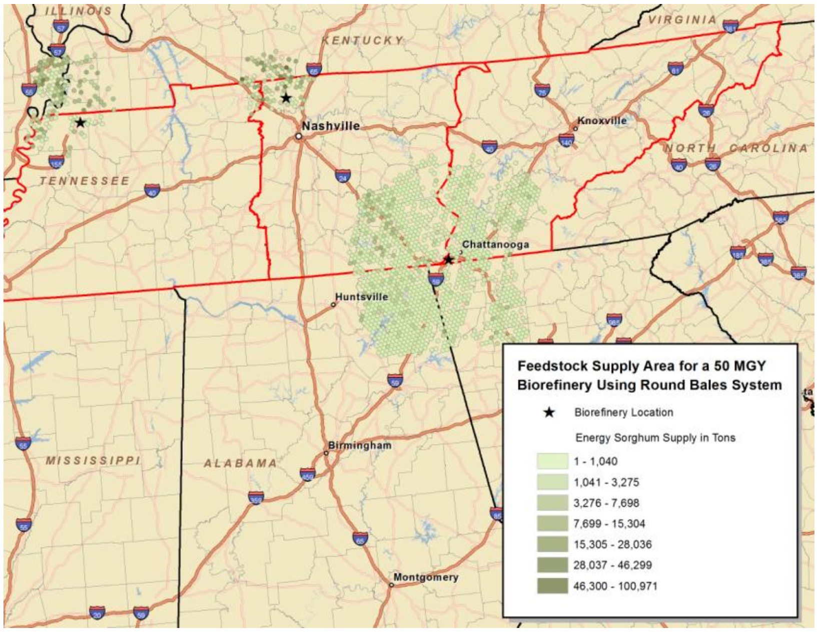

Figure 15. Energy sorghum supply area for a 50-MGY biorefinery using round bales

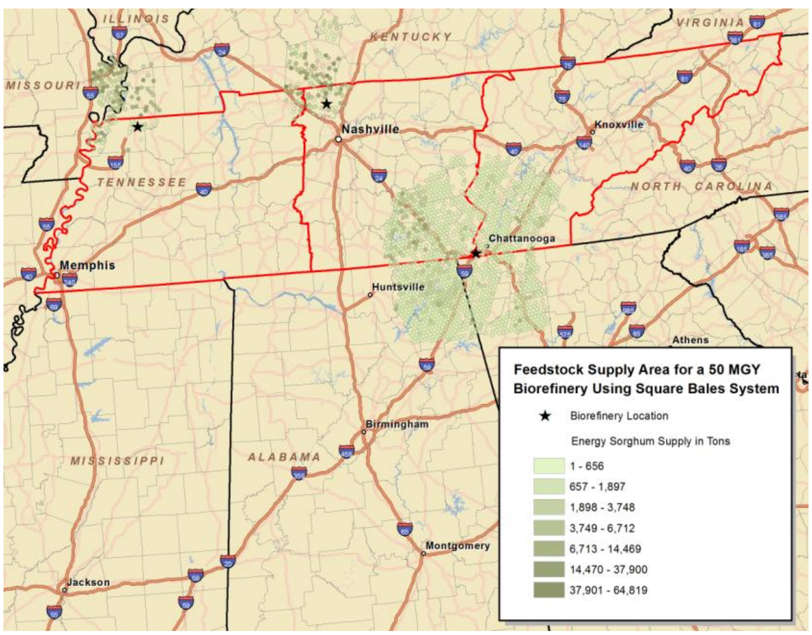

Figure 16. Energy sorghum supply area for a 50-MGY biorefinery using square bales

The emissions of the base case and the link cases for the optimal biorefinery site using LRB or LSB systems by region are presented in Table 8. Driven by the much larger draw area, the VMTs of hauling energy sorghum to the biorefinery in Hamilton County was the highest (5.6 million miles for total), followed by the site in Obion County and Robertson County. Given the least miles traveled for hauling energy sorghum to the biorefinery in central Tennessee and transportation efficiency of square bales, the smallest additional emissions were produced from delivering square bales of energy sorghum to the site in Robertson County. The emissions of NO_x, CO_2, PM_{10} and $PM_{2.5}$ increased about 45 tons, 4,872 tons, 3 tons and 2 tons per year, respectively, in those nine feedstock supplying counties. In contrast, to provide identical amount of biofuels per year, hauling energy sorghum to the biorefinery in Hamilton County under the LRB system produced about 137 tons of NO_x, 14,500 tons of CO_2, 8 tons of PM_{10} and 7 tons $PM_{2.5}$, in total annually in 36 related counties.

Table 8. Trucking Emissions from Hauling Energy Sorghum to a 50-MGY Biorefinery by Supply Chain System and Region in Tennessee

	LRB*			LSB*		
	East	Central	West	East	Central	West
Biorefinery location	Hamilton	Robertson	Obion	Hamilton	Robertson	Obion
# of counties related	36	9	13	36	9	13
Average road slope	2.53	2.39	1.37	2.50	2.13	1.26
VMTs (miles)	5,619,182	2,100,459	3,365,914	4,385,400	1,877,252	3,005,529
Base case (tons)						
NO_x	55,402	26,542	9,508	55,402	14,816	9,594
CO_2	15,261,441	8,149,888	2,448,758	15,261,441	4,010,772	2,435,691
PM_{10}	2,307	1,235	377	2,307	617	378
$PM_{2.5}$	1,757	898	296	1,757	474	298
Link case (tons)						
NO_x	137.2	50.4	77.1	107.4	44.8	68.8
CO_2	14,481.2	5,472.8	8,475.2	11,373.7	4,872.1	7,578.0
PM_{10}	7.5	3.0	4.6	5.9	2.6	4.1
$PM_{2.5}$	6.7	2.7	4.1	5.3	2.4	3.7
Emission increase (%)						
NO_x	0.25	0.19	0.81	0.19	0.30	0.72
CO_2	0.09	0.07	0.35	0.07	0.12	0.31
PM_{10}	0.32	0.24	1.23	0.26	0.43	1.10
$PM_{2.5}$	0.38	0.30	1.39	0.30	0.50	1.24

*LRB: large round bale system, LSB: large square bale system

Figure 17 summarizes both plant-gate cost and hauling emissions of energy sorghum for three sites using two feedstock supply systems in Tennessee. Obviously, for supplying 50 million gallons of biofuel per year that derived from energy sorghum, east Tennessee was not a preferred site to locate the biorefinery since both feedstock cost and vehicle emissions of feedstock hauling were significantly higher than the sites in the central and western regions. For the biorefinery using a large square bale system in Robertson County in the central region, the total plant-gate cost of feedstock was nearly $1 million (or $2 per dry ton) higher than for the site in Obion County in west Tennessee; however, the CO_2 emissions generated from hauling feedstock to the former site was nearly 2,700 tons per year less than the one in west Tennessee. Therefore, it may be intuitive for investors in the biofuel sector to consider the site in Obion County for the biorefinery from the cost minimization perspective. However, from an environmental perspective, the site in Robertson County seems to be sensible particularly under the context of potential biorefinery capacity expansion. The emissions from feedstock hauling will increase even more along with the higher demand for feedstock (see the output in the next section). In addition, the site in central Tennessee could be more attractive if some environmental taxes or payments, such as carbon tax payment, were imposed in the future.

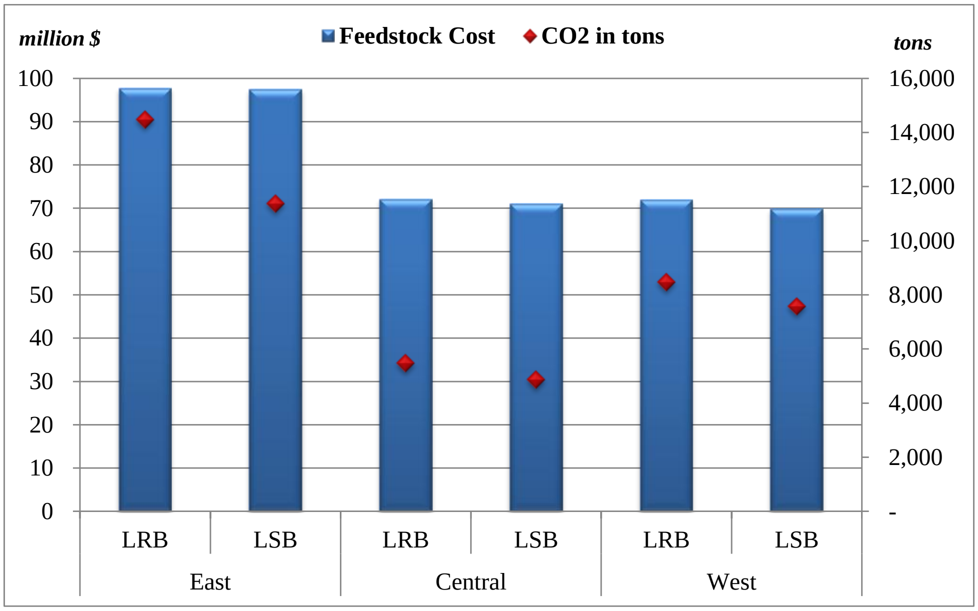

Figure 17. Total plant-gate costs and hauling emissions (CO_2) of energy sorghum to a 50-MGY biorefinery using alternative supply chain systems by region in Tennessee

Capacity of 75 million gallons per year (MGY)

Similar to the 50-MGY biorefinery case, the plant-gate cost of energy sorghum for a 75-MGY biorefinery in Table 9 was at least $107 per dry ton regardless the evaluated supply chain system and study region in Tennessee, which is much more expensive than the plant-gate cost of switchgrass ($70−$75 per dry ton in Table 5). For the biorefinery located in east Tennessee, the production cost, which accounted for more than 50% of total feedstock cost, was considerably higher than other sites because more crop land was needed due to lower yield of energy sorghum in this area (see Figure 4). The biorefinery located in west Tennessee using square bales was suggested to be the one with the least cost feedstock for biofuel production (about $106 million in total or $107 per dry ton).

The feedstock draw area and the biorefinery location for LRB and LSB systems are shown in Figures 18 and 19, respectively. As previously mentioned, the optimal location of the biorefinery in each region was at the state's border. Similar to the 50-MGY biorefinery case, the draw area of energy sorghum for the site in east Tennessee was the largest due to the unavailability of crop land. The feedstock draw area for the site in Hamilton County in the eastern region was clearly truncated by the boundary of assumed feedstock supply area in Figure 1. Most of energy sorghum used in the biorefinery in central and west Tennessee was supplied from the surrounding states given the yield difference between Tennessee and the neighboring states. Specifically, the density of feedstock production in the crop zones in southeastern Missouri was the main feedstock area for the biorefinery in Obion County.

Table 9. Plant-gate Cost of Energy Sorghum for a 75-MGY Biorefinery

	LRB*			LSB*		
	East	Central	West	East	Central	West
Storage option (top/bottom)	tarp/ground			tarp/wood pallet		
Total Feedstock Cost (million $)	$ 155.3	$ 109.5	$ 109.0	$ 156.1	$ 107.8	$ 105.8
Production	$ 79.7	$ 45.9	$ 43.3	$ 86.2	$ 48.6	$ 44.3
Harvest	$ 44.4	$ 40.7	$ 39.2	$ 42.6	$ 38.3	$ 36.5
Storage	$ 2.8	$ 2.8	$ 2.8	$ 5.0	$ 5.0	$ 5.0
Transportation	$ 28.4	$ 20.1	$ 23.7	$ 22.3	$ 15.8	$ 20.0
Feedstock Cost/dt	$ 157	$ 111	$ 110	$ 158	$ 109	$ 107
Biorefinery Location	Hamilton	Robertson	Obion	Hamilton	Robertson	Obion
Total Harvested Area	154,097	128,356	118,162	163,706	148,572	123,842

* LRB: large round bale system; LSB: large square bale system

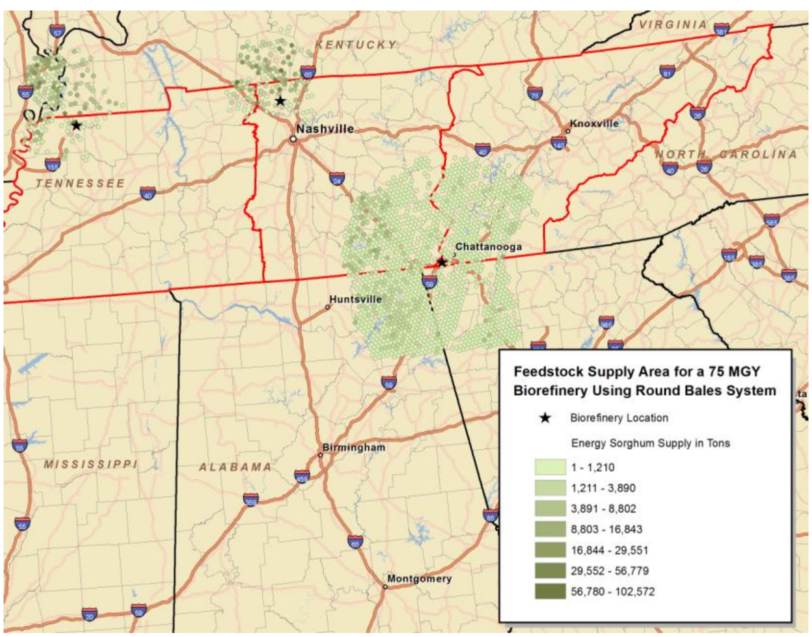

Figure 18. Energy sorghum supply area for a 75-MGY biorefinery using round bales

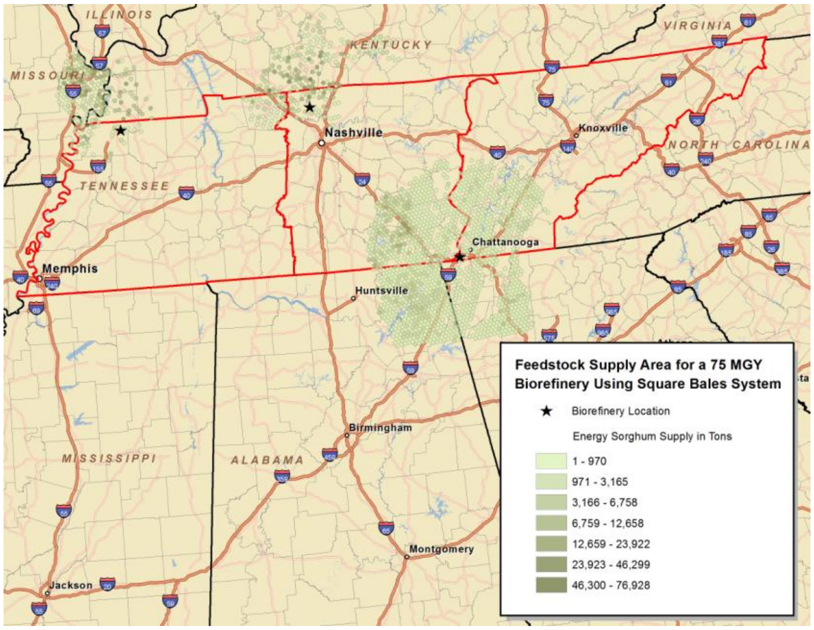

Figure 19. Energy sorghum supply area for a 75-MGY biorefinery using square bales

The emissions in the base case and the link case of the feedstock supply counties for the 75-MGY biorefinery in each region by feedstock supply chain system are summarized in Table 10. The relative level of emissions of feedstock hauling between study regions and feedstock supply chain systems remains the same as observed in the 50-MGY case. The most emissions produced from hauling energy sorghum to the biorefinery were associated with the site in Hamilton County using a large round bale system whereas the least emissions from feedstock transportation were produced for the biorefinery using square bales in central Tennessee.

The plant-gate cost and hauling emissions of energy sorghum to a 75-MGY biorefinery across three regions in Tennessee are presented in Figure 20. Similar to the findings in the 50-MGY biorefinery using energy sorghum as feedstock, it was not cost effective to locate an energy sorghum-based biorefinery in east Tennessee given the substantial cost and hauling emissions of feedstocks. The biorefinery using large square bale system in the west region had the lowest plant-gate cost of feedstock whereas the CO_2 emissions produced from hauling energy sorghum square bales to the biorefinery in Robertson County in central Tennessee was the least among three regions. The decision of the location of an energy sorghum-based biorefinery in Tennessee will be related to the tradeoffs in the plant-gate cost and hauling emissions of the feedstock.

Table 10. Trucking Emissions from Hauling Energy Sorghum to a 75-MGY Biorefinery by Supply Chain System and Region in Tennessee

	LRB*			LSB*		
	East	Central	West	East	Central	West
Biorefinery location	Hamilton	Robertson	Obion	Hamilton	Robertson	Obion
# of counties related	36	11	15	36	15	15
Average road slope	2.50	2.05	1.25	2.51	2.51	1.19
VMTs (miles)	8,349,890	3,732,809	5,007,158	6,752,720	3,342,028	4,884,489
Base case (tons)						
NO_x	55,402	32,611	12,007	55,402	35,769	11,880
CO_2	15,261,441	9,680,941	3,099,326	15,261,441	10,549,122	3,044,291
PM_{10}	2,307	1,476	478	2,307	1,605	470
$PM_{2.5}$	1,757	1,086	374	1,757	1,185	370
Link case (tons)						
NO_x	204.5	89.0	114.4	165.3	79.9	111.7
CO_2	21,600.9	9,646.4	12,676.7	17,437.7	8,666.8	12,328.5
PM_{10}	11.2	5.2	6.9	9.0	4.7	6.8
$PM_{2.5}$	10.1	4.7	6.2	8.1	4.2	6.0
Emission increase (%)						
NO_x	0.37	0.27	0.95	0.30	0.22	0.94
CO_2	0.14	0.10	0.41	0.11	0.08	0.40
PM_{10}	0.49	0.35	1.45	0.39	0.29	1.44
$PM_{2.5}$	0.58	0.43	1.65	0.46	0.36	1.62

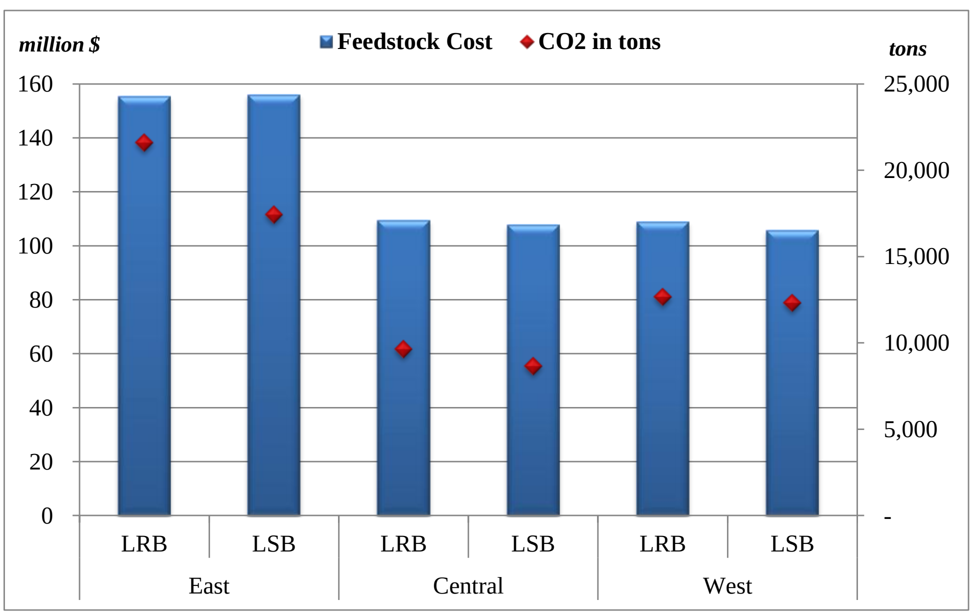

Figure 20. Total plant-gate costs and hauling emissions (CO_2) of energy sorghum to a 75-MGY biorefinery using alternative supply chain systems by region in Tennessee

CONCLUSIONS

Given the quickly evolving interests in the development of cellulosic biofuel in the U.S., the efficiency of the supply chains providing LCB feedstock to refineries is under scrutiny due to the demand for both quality and quantity of the bulky feedstock. In addition, the potential environmental impacts of LCB feedstock transportation has generated increased attention given the potential for significant increases in traffic on the current road system. This study estimated the plant-gate cost and hauling emissions of two feedstocks, switchgrass and energy sorghum, by two commonly utilized feedstock supply chain systems in east, central and west Tennessee. A spatial-oriented mathematical programming model linked to a GIS resource model was used to determine the optimal location of a single-feedstock biorefinery, associated feedstock draw area and delivery schedule on the road network for two potential sizes of biorefineries, 50 and 75 million gallons per year, by minimizing the total plant-gate costs, including the cost of production, harvest, storage, and transportation. Based on the output, U.S. EPA's MOVES model was used to estimate the emissions of the current traffic and the additional trucking traffic from feedstock transportation in those counties supplying feedstock for biofuel production.

Our results indicate that the plant-gate cost of LCB feedstock is influenced by the yield of the feedstock, available crop land, opportunity cost of converting traditional crops to the feedstock, and the efficiency of harvesting, storing and transporting feedstock. From an economic standpoint, switchgrass is found to be more feasible as a feedstock when compared to energy sorghum for cellulosic biofuel production in Tennessee. The significant higher plant-gate costs of energy sorghum are primarily driven by its production cost. In essence, the inputs required to produce an annual crop (energy sorghum) are more than for a perennial grass (switchgrass). Also, short of available crop land and the less fertile soil area, particularly in east Tennessee, generate a larger feedstock draw area, hence increasing transportation cost. In terms of the performance of the two evaluated supply chain systems, the efficiency in harvesting and transporting large square bales makes them more cost competitive than the large round bale system for biofuel production. For the switchgrass feedstock, among all three regions, the biorefinery with the most economical feedstock cost was positioned in the Robertson County in central Tennessee.

Additional truck traffic from LCB feedstock hauling produced more emissions in the study region. Comparing the trucking emissions, hauling energy sorghum to the biorefinery creates significant more pollutants than delivering switchgrass. The higher emission level is related to substantial vehicle travel miles associated with energy sorghum deliveries caused by the larger feedstock draw area. Hauling switchgrass to the optimal site in west Tennessee using large round bale system produces the greater emissions, while the least emissions are generated from hauling large square bales to the optimal site in central Tennessee. Based on the estimated additional 1.2 million VMTs of feedstock transportation to the biorefinery in Robertson County, the emissions of NO_X, CO_2, PM_{10}, and $PM_{2.5}$ for the eight feedstock supplying counties increase by 0.12%, 0.04%, 0.15%, and 0.18%, respectively, when compared with the overall baseline emissions. Along with the output of plant-gate cost, our findings suggest that the biorefinery located in Springfield, Tennessee near the intersection of U.S. Highways 431 and 41 (about 25 miles north of Nashville, Tennessee, and 10 miles from the Kentucky border) is the most preferred site to establish a switchgrass-based biorefinery.

This study illustrates the emission impacts of hauling the bulky LCB feedstock to a biorefinery. The capacity of the biorefinery will affect the volume of traffic, hence emissions. In addition, a key assumption used in this analysis is that the biorefinery only converts single feedstock (either switchgrass or energy sorghum) for biofuel. The total feedstock cost and emissions may change when the biorefinery can process multi-feedstocks since feedstock inventory will be lower if various LCB feedstocks can be harvested and hauled to the biorefinery in different periods throughout the year. Also, the capability of processing diverse LCB feedstocks may reduce the feedstock draw area; thus lowering the transportation costs and hauling emissions. The analytical framework developed in this study can be applied to evaluate various feedstocks logistic and harvest systems and compare their emissions and plant gate costs associated with each system. The knowledge of both the economic cost and emission impact can help regions, state, or the nation develop a sustainable LCB-based biofuel industry.

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