Modeling the Air Quality Impacts of Feedstocks Transportation for Cellulosic Biofuel Production in Tennessee

T. Edward Yu¹ (Corresponding author)
E-mail: tyu1@utk.edu

Burton C. English¹
E-mail: benglish@utk.edu

James A. Larson¹
E-mail: jlarson2@utk.edu

Joshua S. Fu²
E-mail: jsfu@utk.edu

Daniel De La Torre Ugarte¹
E-mail: danieltu@utk.edu

Jeongran Yun²
E-mail: jyun@utk.edu

Jimmy Calcagno, III²
E-mail: jacal@utk.edu

Bradly Wilson¹
E-mail: driver8@utk.edu

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¹Department of Agricultural & Resource Economics, University of Tennessee, Knoxville, TN 37996-4518, Phone: (865) 974-7231, Fax: (865) 974-7484

²Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, TN 37996-4518, Phone: (865) 974-2629, Fax: (865) 974-2669
Abstract   This study estimates the plant-gate cost and hauling emissions of supplying two different biomass feedstocks, a perennial grass (switchgrass) and an annual energy crop (energy sorghum), for biofuel production in Tennessee. This study first applied a spatial-oriented mixed-integer mathematical programming model using GIS data to generate a least-cost solution of the feedstock supply system and the location of a single-feedstock biorefinery in three different regions of the state, i.e. east, central and west Tennessee. Based on the feedstock draw area and the road links for hauling feedstock to the biorefinery in each region determined in the model, US Environment Protection Agency’s Mobile Vehicle Emission Simulator (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 the degree of feedstock draw area dispersion and topography of draw area around the biorefinery site have important impact on the emissions produced from hauling feedstock to the biorefinery. Based on feedstock plant-gate cost and hauling emissions, switchgrass is more suitable than energy sorghum for biofuel production in Tennessee. The larger draw area associated with energy sorghum creates higher vehicle travel miles, resulting in more transportation costs and hauling emissions to the biorefinery. The biorefinery with the most economic feedstock cost and the least feedstock hauling emission is suggested to be sited in Robertson County in central Tennessee.

Keywords: biofuel, feedstock transportation, hauling emissions, MOVES model
INTRODUCTION

Lignocellulosic biomass (LCB) produced from dedicated energy crops and the residues of crop and forest have great potential for the production of bio-based fuels, power, and products in the United States. Various federal policy programs, such as blender tax credits, federal legislation of biofuel mandates enacted in 2007, and the grant/loan program for establishing biomass feedstocks and constructing LCB-based biofuel refineries under the Food, Conservation, and Energy Act of 2008, have been enacted to accelerate the commercialization of advanced biofuels, including biofuels generated from LCB feedstock. The development of a LCB-based value chain is also a major focus of bioenergy sector development in many states. Among others, the Tennessee Biofuels Initiative (TBI) is a state sponsored program committing $70 million in 2007 to develop a biofuels sector using LCB feedstocks in Tennessee. The development of conversion technologies for LCB-based biofuel production at a pilot biorefinery that was created under TBI has stimulated the discussion about establishing a commercial-scale biorefinery in Tennessee in the near future (1).

The amounts of LCB feedstocks needed to supply a commercial-scale biorefinery will be significant as the LCB feedstock generally has low density. Also, most of the potential lands for LCB feedstock production in Tennessee are currently idled or are in less transportation-intensive traditional crop activities. Converting those lands to LCB feedstock production implies increased traffic on roadways that link the fields and the biorefinery. Since more truck traffic of hauling LCB feedstock production is expected for an industrialized biofuel sector, one potential sustainability issue is increased vehicle emissions from hauling feedstock to the biorefinery. This environmental issue is presumably important since road transport is considered one of the main sources of air pollution. According to U.S. Environment Protection Agency, heavy duty trucks accounted for 50%, 56%, and 68% of the NOx, particulate matter (PM10), and fine particle (PM2.5) emissions, respectively, produced by all vehicles on highways in 2005 (2). The environmental impacts of increased traffic induced by LCB feedstock shipments have receiving increasing attention in recent literature (e.g. 3, 4). Jäppinen et al. (5) stated that it is crucial to consider the local conditions, including the properties of the transport network for hauling feedstock, when evaluating the sustainability of biomass-based energy production. This may be important in Tennessee and the Southeast where the landscape and road system are more complex when compared to the Midwest and thus may impact emissions.

Given the potential for developing a biomass-based biofuel industry in Tennessee, this study evaluates the emissions produced from hauling alternative LCB feedstocks to the optimal sites of a biorefinery that have the least plant-gate cost of feedstock in several regions of the state. Our specific research objective is to develop a comprehensive estimate of vehicle emissions caused by the delivery of LCB feedstock to a commercial-scale biorefinery site using the latest vehicle emission model by U.S. Environmental Protection Agency (EPA). Two LCB feedstocks, switchgrass and energy sorghum, are evaluated. Switchgrass is a perennial grass which can be planted on both pasture and crop lands, while energy sorghum as an annual crop is generally cultivated on traditional crop land. The difference in land conversion will presumably affect the land use change for feedstock production and the dispersion of feedstock draw area, which consequently influences the hauling emissions of feedstock. The evaluation of the hauling emissions associated two LCB feedstocks in different regions can offer some insights of the impact of crop system and spatial attributes on the emissions of feedstock transportation.
METHODS AND DATA

The analysis of plant-gate costs of switchgrass feedstock and vehicle emissions from hauling 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.

The assumed capacity of the commercial-scale biorefinery is 50 million gallons (189.25 kl) per year of biofuel. 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 square bale harvest, storage, and transportation systems, which is commonly used for the harvest and storage of hay and can also be used for switchgrass in Tennessee (6). The potential feedstock supply area assumed in the analysis includes Tennessee and a buffer area within 50 miles (80.5 km) adjoining the state border. The three geographic (eastern, central and western) regions in Tennessee that were used in the analysis were defined by University of Tennessee Extension (7). 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 1).

FIGURE 1 Potential industrial parks to site the biorefinery in three Tennessee geographic regions used in the analysis
Determining the Biorefinery Location, Feedstock Draw 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 LCB feedstock to the biorefinery, subject to constraints 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 (6). A complete description of the BESTA model is available in Gao (8).

The BESTA model uses detailed spatial data from a GIS model, the Biofuels Facility Location Analysis Modeling Endeavor (BioFLAME) (9). 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 LCB feedstock production. To determine the potential area for LCB feedstock in each crop zone, a price of each LCB feedstock 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 (9).

The street level network was applied to estimate transportation costs of LCB feedstock 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.

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 square bales are then placed into storage at the edge of the field until transported to biorefinery. Storage protection was not applied to the 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 square bale system were modeled using estimated losses by time in storage for switchgrass from Mooney et al. (6). Labor costs plus operating and ownership costs for equipment and vehicles were obtained from Gao (8) and Larson et al. (10).

Traditional crop yields were from the SSURGO database at the sub-county level (11). Areas in each traditional crop for each crop zone were from the cropland layer database (12).
Switchgrass and energy sorghum yields were obtained from the POLYSYS model (13). The yield of mature switchgrass ranges between 8.0 and 9.4 dt/acre, while the yield of mature energy sorghum after adjusting the lodging problem during harvest was estimated around 6.0−9.0 dt/acre. The data for traditional crop prices used in the BESTA and BioFLAME models was for the 2010 crop year (12).

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.

Determining Truck Traffic Emissions from Feedstock Hauling

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. The version of the program that was used in this study is MOVES2010a (hereafter referred to as MOVES). 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 (referred to as the base case). 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 large square bales collection, harvest, storage and transportation system (referred to as the link case).

In the 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 (95 counties) was selected in turn, as well as the border counties (188 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 particulate matter less than 10 microns in aerodynamic diameter (PM$_{10}$) and less than 2.5-microns (PM$_{2.5}$), and the equivalent CO$_2$. Total NO$_x$ is the summation of nitrogen oxide (NO) and nitrogen dioxide (NO$_2$). 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).

When evaluating the truck emissions from feedstock hauling in the link case, the Project scale was selected which permits the modeling of emission effects from individual road links that can be spatially connected to one another. The calendar year in the model were same as those
selected for the base case (i.e., 2010). A representative month of the year that characterized each
season of the year (i.e., April, July, October, and January) was used in the model to save
computational time. In addition, only weekdays were modeled assuming deliveries typically
occur Monday through Friday. The time between 11:00AM and 11:59AM was used as the
representative hour of trucking delivery. Additionally, 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. A road source type link file was created for input to the model. The link volume was for
a single 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%. Each link length was 10 miles long. The combination short-haul truck was selected as
the link source type which is a tractor-trailer type vehicle configuration. 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 NOx Pollutant Processes. In addition,
brake wear and tire wear were selected for PM emissions.

The output data were post-processed by aggregating the emission rate per distance for
each air pollutant. The results contained emission rates for each air pollutant in units of grams
per mile for the link length 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., those representative
counties selected) for each of the four seasons of the year (i.e., spring, summer, fall, and winter).
These emission factors were then used in the supply chain algorithms to approximate increases in
emissions due to the additional truck traffic necessary to transport feedstock between farms and
biorefinery.

RESULTS

Biorefinery Location, Feedstock Draw Area and Delivery Schedule

Table 1 presents the total cost of switchgrass and energy sorghum for a biorefinery with the
capacity of 50 million gallons (189.25 kl) year−1 (50 MGY) using the large square bale harvest
system. The least-cost storage system was storing switchgrass and energy sorghum on the woody
pallets with a tarp. Consistent with the partial budgeting results by Mooney et al. (6), the value of
the dry matter preserved using tarps and pallets for protection offset the costs of protection with
the large square bale system. The total cost for delivering about 658,000 tons (596,555 dry Mg)
year−1 of large square bales of switchgrass to the least-cost site in each of the three regions
ranged between $45.4 million and $46.4 million. The cost of harvest of square bales accounted
for more than half of the total plant-gate cost, while transportation costs and production cost
were estimated at about 20% each of total cost in the system.

Compared to the plant-gate cost of switchgrass, energy sorghum is a more expensive
feedstock to produce in Tennessee. The total plant-gate costs 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 using the same storage method in the same 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. In addition, the transportation cost of
hauling energy sorghum to the biorefinery in east Tennessee was higher than for the sites in the
TABLE 1 Total Plant Gate Costs of Switchgrass and Energy Sorghum Using the Large Square Bale Harvest and Logistic System

<table>
<thead>
<tr>
<th>Storage option (top/bottom)</th>
<th>Switchgrass</th>
<th>Energy Sorghum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East</td>
<td>Central</td>
</tr>
<tr>
<td>Total Feedstock Cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(million $)</td>
<td>$46.3 $</td>
<td>$45.4 $</td>
</tr>
<tr>
<td>Production</td>
<td>$9.2 $</td>
<td>$9.3 $</td>
</tr>
<tr>
<td>Harvest</td>
<td>$23.9 $</td>
<td>$23.9 $</td>
</tr>
<tr>
<td>Storage</td>
<td>$3.3 $</td>
<td>$3.3 $</td>
</tr>
<tr>
<td>Transportation</td>
<td>$9.9 $</td>
<td>$8.8 $</td>
</tr>
<tr>
<td>Feedstock Cost/dt</td>
<td>$70 $</td>
<td>$69 $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biorefinery Location</th>
<th>McMinn</th>
<th>Robertson</th>
<th>Lawrence</th>
<th>Hamilton</th>
<th>Robertson</th>
<th>Obion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Harvested Area</td>
<td>79,715</td>
<td>80,061</td>
<td>79,680</td>
<td>108,613</td>
<td>90,454</td>
<td>82,666</td>
</tr>
</tbody>
</table>

Production cost of energy sorghum was the highest among all cost components since it is an annual crop. Unlike switchgrass as a perennial grass, the demand for input uses applied to annual crop is much higher every year. Transportation cost accounted for about 15-18% of the total plant-gate cost.

The feedstock draw area and biorefinery location in each region for switchgrass and energy sorghum are illustrated in Figures 2 and 3, respectively. For switchgrass (Figure 2), the feedstock draw area in the central Tennessee region was relatively compact than that in the east and west Tennessee; however, the harvested acreage in the draw area was similar in each of the three regions (see Table 1). The total feedstock draw area is influenced by the yield of switchgrass in each crop zone and the availability of the cheaper traditional crops or grasses. As the opportunity cost of converting hay land to switchgrass production is the least among all crops in Tennessee, the available hay land in each crop zone determines the density of switchgrass produced in that spatial unit. Also, the yield of switchgrass in a given crop zone also affects the harvests of switchgrass. Hence, the density of switchgrass production (presented in the color scheme) in some crop zones in the central Tennessee was higher than other crop zones given more available hay area and better yield. Interestingly, the least-cost location of the biorefinery in west Tennessee was actually close to the central Tennessee, which was again affected the availability of hay land. Agricultural lands in west Tennessee are primarily used for grains, oilseeds, and cotton, thus the opportunity costs of converting those high value crops for switchgrass production were too high.

The draw area of energy sorghum by region in Tennessee in Figure 3 depicts 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, suggesting the difficulty of
FIGURE 2  Switchgrass supply area for a biorefinery using square bales by region

FIGURE 3  Energy sorghum supply area for a biorefinery using square bales by region
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 and smaller feedstock draw area. The optimal location of the biorefinery in all three regions 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.

Similarly, the model suggests that south-central Kentucky was the major area supplying energy sorghum to the biorefinery in Robertson County because of 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.

Truck Traffic Emissions in the Base and Link Cases

Table 2 summarizes the emissions in the base case and the link case for the optimal biorefinery using switchgrass and energy sorghum in each region. Because of the Appalachian Mountains, the average slope of the roads in the east was higher than the road slope in the central and west regions. In the base case, the emission inventories in the 17 counties of east Tennessee was the highest, while the 11 counties of west Tennessee Given had the lowest emission inventories. In the link case, switchgrass hauling to the optimal site in west Tennessee generated the highest VMTs (nearly 2.0 million miles or 3.2 million km), while the least VMTs (about 1.2 million miles or 1.9 million km) were produced from feedstock deliveries to the biorefinery in Robertson County. Since the least miles traveled by the trucks and the flatter gradient of road networks in central Tennessee, the biorefinery in Robertson County generated the least emissions 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.

In terms of energy sorghum, since feedstock area covered 36 counties in east Tennessee, the emission inventory ranked the top, while the emission inventory in the west Tennessee was the fewest. Driven by the much larger feedstock draw area, the VMTs of hauling energy sorghum to the biorefinery in Hamilton County in east Tennessee was the highest (4.4 million miles or 7.1 million km 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, the smallest additional emissions were produced from delivering square bales of energy sorghum to the site in Robertson County. The emissions of NOx, CO2, 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 NOx, 14,500 tons of CO2, 8 tons of PM_{10} and 7 tons PM_{2.5}, in total annually in 36 related counties.

Combining the economic and environmental indicators of each site by feedstock provides some insights about the suitability of the feedstock and the optimal biorefinery location that satisfies the development of a sustainable biofuel industry in Tennessee. Figure 4 summarizes both plant-gate costs and CO2 emissions of hauling switchgrass and energy sorghum feedstock to
TABLE 2 Trucking Emissions from Hauling LCB Feedstock to a Biorefinery in Tennessee

<table>
<thead>
<tr>
<th>Biorefinery location</th>
<th>McMinn</th>
<th>Robertson</th>
<th>Lawrence</th>
<th>Hamilton</th>
<th>Robertson</th>
<th>Obion</th>
</tr>
</thead>
<tbody>
<tr>
<td># of counties related</td>
<td>17</td>
<td>8</td>
<td>11</td>
<td>36</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>Average road slope (%)</td>
<td>3.11</td>
<td>2.26</td>
<td>2.64</td>
<td>2.50</td>
<td>2.13</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Base case (tons)

<table>
<thead>
<tr>
<th></th>
<th>Switchgrass</th>
<th></th>
<th></th>
<th>Energy Sorghum</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East</td>
<td>Central</td>
<td>West</td>
<td>East</td>
<td>Central</td>
</tr>
<tr>
<td>NOx</td>
<td>39,036</td>
<td>26,257</td>
<td>11,899</td>
<td>55,402</td>
<td>14,816</td>
</tr>
<tr>
<td>CO2</td>
<td>11,073,869</td>
<td>8,070,270</td>
<td>3,139,225</td>
<td>15,261,441</td>
<td>4,010,772</td>
</tr>
<tr>
<td>PM10</td>
<td>1,676</td>
<td>1,223</td>
<td>480</td>
<td>2,307</td>
<td>617</td>
</tr>
<tr>
<td>PM2.5</td>
<td>1,257</td>
<td>889</td>
<td>375</td>
<td>1,757</td>
<td>474</td>
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Link case

<table>
<thead>
<tr>
<th></th>
<th>Switchgrass</th>
<th></th>
<th></th>
<th>Energy Sorghum</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East</td>
<td>Central</td>
<td>West</td>
<td>East</td>
<td>Central</td>
</tr>
<tr>
<td>VMTs (miles)</td>
<td>1,932,794</td>
<td>1,231,110</td>
<td>1,968,441</td>
<td>4,385,400</td>
<td>1,877,252</td>
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<tr>
<td>NOx (tons)</td>
<td>48.2</td>
<td>30.3</td>
<td>49.4</td>
<td>107.4</td>
<td>44.8</td>
</tr>
<tr>
<td>CO2 (tons)</td>
<td>5,268.1</td>
<td>3,303.4</td>
<td>5,432.5</td>
<td>11,373.7</td>
<td>4,872.1</td>
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<tr>
<td>PM10 (tons)</td>
<td>2.9</td>
<td>1.8</td>
<td>3.1</td>
<td>5.9</td>
<td>2.6</td>
</tr>
<tr>
<td>PM2.5 (tons)</td>
<td>2.6</td>
<td>1.6</td>
<td>2.8</td>
<td>5.3</td>
<td>2.4</td>
</tr>
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Emission increase (%)

<table>
<thead>
<tr>
<th></th>
<th>Switchgrass</th>
<th></th>
<th></th>
<th>Energy Sorghum</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East</td>
<td>Central</td>
<td>West</td>
<td>East</td>
<td>Central</td>
</tr>
<tr>
<td>NOx</td>
<td>0.12</td>
<td>0.12</td>
<td>0.42</td>
<td>0.19</td>
<td>0.30</td>
</tr>
<tr>
<td>CO2</td>
<td>0.05</td>
<td>0.04</td>
<td>0.17</td>
<td>0.07</td>
<td>0.12</td>
</tr>
<tr>
<td>PM10</td>
<td>0.18</td>
<td>0.15</td>
<td>0.65</td>
<td>0.26</td>
<td>0.43</td>
</tr>
<tr>
<td>PM2.5</td>
<td>0.21</td>
<td>0.18</td>
<td>0.74</td>
<td>0.30</td>
<td>0.50</td>
</tr>
</tbody>
</table>

FIGURE 4  Total plant-gate costs and hauling emissions (CO2) of LCB feedstock to a biorefinery using large square bale system by region in Tennessee
the optimal site of a single-feedstock biorefinery in three regions. Obviously, for supplying 50 million gallons of biofuel per year, switchgrass-based biofuels has much lower feedstock cost when comparing to energy sorghum. Similarly, the emissions generated from hauling energy sorghum to the biorefinery were much higher than that associated with hauling switchgrass due to the more dispersed feedstock draw area and the supply location of feedstock. Although the differences in the plant-gate cost of switchgrass among all three regions were small, the emissions produced from delivering feedstock to the biorefinery in the central region were clearly lower than that for other two regions. Thus, the biorefinery using switchgrass as feedstock located in central Tennessee (Robertson County) was found to be the most sustainable with the least economic costs and hauling emissions of feedstock.

CONCLUSIONS

Driven by the increasing 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, in east, central and west Tennessee. A spatial-oriented mathematical programming model utilizing high resolution GIS data was used to determine the optimal location of a single-feedstock biorefinery, associated feedstock draw area and delivery schedule on the road network for a biorefinery with the capacity of 50 million gallons (189.25 kl) 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. 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 more dispersed feedstock draw area, hence increasing transportation cost.

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 central Tennessee using produces the least emissions. Based on the estimated additional 1.2 million VMTs of feedstock transportation to the biorefinery in Robertson County, the emissions of NOx, CO2, PM10, and PM2.5 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 in Robertson County,
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.
REFERENCES


