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Dedicated Energy Crop Supply Chain and Associated Feedstock Transportation Emissions: A Case Study of Tennessee

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This study minimizes total cost for single-feedstock supply chains of two dedicated energy crops, perennial switchgrass and biomass sorghum, in Tennessee using a spatial optimization model. Greenhouse gas emissions from the transport of feedstock to the conversion facility were estimated for respective feedstock supply chains. Results show that different demand for land types from two feedstocks and the geographically diverse landscape across the state affect the economics of bioenergy crops supply chains and feedstock transportation emissions. Switchgrass is more suitable than biomass sorghum for biofuel production in Tennessee based on the supply chains cost and feedstock hauling emissions.

INTRODUCTION

Biomass feedstock 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 (Turhollow et al. 2014). Various federal policy programs, such as blender tax credits, federal legislation of biofuel mandates, and the grant/loan program for establishing biomass feedstocks and constructing conversion facilities under the Food, Conservation, and Energy Act of 2008 (i.e., 2008 Farm Bill), have been implemented to accelerate the commercialization of advanced biofuels. The development of biomass-based value chains is also a major focus of bioenergy sector development in many states. Among others, the Tennessee Biofuels Initiative (TBI) is a state sponsored program to foster the development of the biofuels sector using switchgrass in Tennessee (Tiller 2011). The current progress of conversion technologies for cellulosic biofuel production at a pilot facility created under the TBI has motivated discussion about developing a commercial-scale cellulosic biofuel plant in Tennessee.

The amounts of biomass required to supply a commercial-scale conversion facility are significant given that biomass has low energy density. In addition, most of the potential lands for biomass production in Tennessee are currently idled or are used for less transportation-intensive traditional crop activities, such as pasture. Converting agricultural lands to biomass production implies additional traffic on roadways that connect fields and the conversion facility. Because more truck traffic to haul biomass is expected for an industrialized biofuel sector, one related potential environmental issue is increased emissions from hauling feedstock to the conversion facility. This environmental issue is presumably important because road transportation is a major source of greenhouse gas (GHG) emissions (Fürst and Oberhofer 2012).

Switchgrass and biomass sorghum have been considered as potential feedstocks for biofuel production in the southeast region (Turhollow et al. 2014). Switchgrass has consistent yields over diverse weather conditions and requires relatively low inputs compared with field crops (Wright and Turhollow 2010). Biomass sorghum also performs well in a wide range of soil types and drought conditions (Rooney et al. 2007). Both energy crops are capable of producing high biomass yields on marginal soils common to the region, including Tennessee. Switchgrass is a perennial grass which can be planted on pasture and croplands, while biomass sorghum as an annual crop is generally cultivated on cropland. In Tennessee, croplands are primarily located in the west side of the state given the flat terrain near the Mississippi River, while hay and pasturelands are common in the eastern region because of the varied topography related to the Appalachian Mountains. Different demand for land types from two energy crops and the geographically diverse landscape across the state presumably have different effects on land use for feedstock production and the dispersion of the feedstock draw area in Tennessee, which consequently influences the emissions from trucking feedstock to the conversion facility.

Given the potential for developing a biomass-based bioenergy industry in Tennessee, this study aims to achieve two objectives: 1) to evaluate the economics of the two dedicated energy crops' supply chains in various regions of the state, and 2) to assess the transportation emissions produced from hauling biomass feedstocks to the conversion facility with the least-cost supply chains by region identified in Objective 1. Our analysis generates insights regarding the impacts of crop systems and spatial characteristics on feedstock cost and GHG emissions of feedstock transportation in different regions. This information can benefit bioenergy sector stakeholders, including farmers, private investors, local communities, and regional development agencies.

LITERATURE REVIEW

Economics of biomass supply chains has been a major focus in the literature of bioenergy because the cost of feedstock supply chains is very influential to the commercialization of cellulosic biofuels (Hess et al. 2007). The biomass feedstock supply chain includes activities of feedstock production, harvest, storage, and transportation from field to conversion facility. The delivered cost of biomass feedstock can be influenced by the characteristics at each step of the supply chain, such as the type of harvesting method (e.g., bale or chop), choice of preprocessing operation (e.g., compression, pelletization), storage method used (e.g., outdoor or indoor), and mode of transportation (e.g., truck, rail, ocean). An extensive survey of recent literature in economic analysis of biomass and biofuel supply chains can be found in Sharma et al. (2013) and Mafakheri and Nasiri (2014). A brief review of the studies focusing on the transportation element in feedstock and biofuel supply chains is offered in this section.

Cundiff et al. (1997) developed a two-stage linear programming model to minimize the delivery cost of switchgrass through scheduling management for an ethanol plant in Virginia. Considering feedstock yield variations during different growing and harvest conditions, their findings suggest that average transportation cost was approximate \$8−\$10/dry metric ton (Mg) for an average travel distance of 22 km. Morrow et al. (2006) developed a transportation distance optimization model to minimize costs of distributing a range of ethanol blends (E5, E10, and E16) to U.S. metropolitan areas. They concluded that pipeline is the most cost effective means for ethanol transportation and emphasized the importance of an efficient transportation system for the competitiveness of the U.S. biofuel industry. Ekşioğlu et al. (2010) applied a mixed-integer programming model to minimize the delivery cost of biofuels by determining the mode use, shipment schedule, shipment size, production, and inventory schedule in a Mississippi case study. Barge and rail were considered for feedstock transportation and their results showed that barge is a more economic mode when demand for feedstock increases. Roni et al. (2014) analyzed the rail cost of biofuel and biomass using Surface Transportation Board's Waybill data, and derived the relationship between rail cost and car type, shipment size, commodity type, and rail movement type for both biofuel and biomass.

A number of studies have applied a geographic information system (GIS) to locate the potential sources of feedstock, determine location of biorefineries, and assess the transportation cost of feedstock or biofuel. Khachatryan et al. (2009) applied GIS to examine the availability of agricultural crop residue for cellulosic ethanol in the state of Washington and estimated the feedstock farm gate cost and transportation cost. They derived a supply curve of feedstock and suggested that plant capacity, transportation distances, and fuel price are influential to feedstock cost. Freppaz et al. (2004) integrated the GIS tool and mathematical programming in a Decision Support System to evaluate the availability of forest biomass and determine the location and size of plants in Val Bormida, Italy. Their results showed that local biomass availability can support 16% of energy need in the region at a reasonable cost. Marvin et al. (2012) estimated the net present value of a biomass-to-ethanol supply chain using a mixed-integer programming model and spatial data. Considering five agricultural residues in nine states in the U.S. midwest, the model determined the optimal locations and capacities of biofuel plants and biomass harvest and distribution. Using high resolution spatial data in Tennessee generated from GIS, Larson et al. (2015) assessed the plant gate cost of switchgrass using a mixed-integer programming model and evaluated the impact of dry matter loss during storage on the distribution of feedstock. They concluded that the storage loss is influential to the schedule of feedstock delivery and pattern.

More recent attention has been drawn to the environmental or social impacts of increased traffic induced by biomass feedstock supply chains. For instance, Kumar et al. (2006) suggested that the projected increase in truck traffic is likely to increase public resistance if the plant is located close to a community, and that rail transport reduces the number of loads and produces less emissions and congestion. Mahmudi and Flynn (2006) found that while rail shipments of biomass feedstock reduces emissions and congestion, it is not economical unless the shipping distance exceeds 120 miles. Tyner and Rismiller (2010) evaluated the impact of establishing a cellulosic biofuel industry on local road infrastructure in Indiana and suggested that considerable truckloads and high vehicle trip miles (VTM) surrounding each biofuel plant are anticipated. Moreover, the cellulosic biofuel industry would generate two to five times more VTM per gallon of biofuel, or up to 255% more ton-miles per gallon of biofuel compared with the existing grain-based biofuel industry. Jäppinen et al. (2011) indicated that it is crucial to consider local conditions, including the properties of the transportation network for hauling feedstock, when evaluating the sustainability of biomass-based energy production. Jäppinen et al. (2013) evaluated two case studies of wood chips supply chains and found that rail transportation to supplement direct truck transportation for wood chips may reduce supply chain GHG emissions. Also, biomass availability and modes of transportation to a given site should be taken into account when assessing GHG emissions in a biomass supply chain.

The aforementioned studies have highlighted the importance of the transportation sector in an efficient biomass and biofuel supply chain, and the concern of environmental and social impact of high traffic volume related to feedstock transportation. The current study complements the literature by analyzing the impacts of diverse crop systems and spatial characteristics on feedstock transportation cost and GHG emissions through an empirical study of comparing two potential energy crops (switchgrass and biomass sorghum) in Tennessee.

METHODS AND DATA

The analysis of supply chain costs of switchgrass and biomass sorghum and GHG emissions from transporting the feedstock to a conversion facility was divided into two major steps. First, the least-cost feedstock draw area and location of the conversion facility was identified for each of three regions in Tennessee (eastern, central, and western) by the Bioenergy Site and Technology Assessment (BeSTA) model developed in Larson et al. (2015). The cost-minimization solution located the most efficient road links within the feedstock draw area to the biorefinery based on the real road network for each region. Second, the additional emissions produced from feedstock transportation were estimated by applying an emission modeling system developed by the U.S. Environmental Protection Agency (US EPA 2012) to the vehicle traffic flow data generated in the first step.

The capacity of the commercial-scale conversion facility was assumed to be 50 million gallons per year (MGY) of biofuel (Tembo et al. 2003). The conversion facility considered in this study was a single-feedstock conversion facility that would not process mixed feedstock. Supply chain costs were evaluated for large rectangular bale harvest, storage, and transportation, a commonly used system for the harvest and storage of hay that can also be used for switchgrass (Mooney et al. 2012). The potential feedstock supply area includes Tennessee and a buffer area of 50 miles along the state's border to allow facilities to source feedstock from adjacent states if biofuel plants are sited near the border. Three geographic regions (eastern, central, and western) capture the spatial variations as defined by University of Tennessee Extension (University of Tennessee 2014). The potential locations for conversion facilities 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.

Step 1: Determining Dedicated Energy Crops Supply Chains

The BeSTA model is a spatially oriented mixed-integer programming model that considers the sequence of production, harvest, storage, and transportation activities on a monthly basis within a year (Larson et al. 2015). The BeSTA model incorporates spatial variations and the within-year dynamics of switchgrass operations in the optimization of biomass feedstock supply chains, including location of the conversion facility, feedstock draw area, and feedstock delivery routes. The model objective function is to minimize opportunity cost of land, production cost, harvest cost, storage cost, and transportation cost of biomass feedstock to the conversion facility.

Certain constraints related to feedstock production, harvest, storage, and transportation activities were imposed in the BeSTA model. The annual supply of feedstock was constrained by feedstock yields and harvested area. In addition, monthly feedstock harvested in each land were subject to feedstock yields and available harvested area in the land unit. Moreover, total monthly harvested feedstock was limited by available harvest hours and machine availability. Constraints were also imposed on storage and transportation in each month. Monthly harvested feedstock was larger than feedstock shipped to the conversion facility after adjusting dry matter losses during transportation. Monthly harvested feedstock also must be greater than feedstock placed into storage in each month of harvest season. Delivered feedstock could not exceed accumulated storage of feedstock. In addition, feedstock deliveries were assumed to meet ethanol production each month. Additional constraints on the mass balance between harvest and inventory were imposed in the model. Details on the mathematical equations of the BeSTA model can be found in the Appendix.

Detailed spatial data were used for the supply chain analysis. The potential feedstock draw area was disaggregated into a vector database of contiguous five-square-mile land resource units based on remote sensing data within the feedstock supply regions. Public lands in the region were excluded from the analysis. The land resource units are the geographic units used to model areas in existing agricultural production activities (e.g., barley, corn, cotton, hay, oats, pasture, soybean, sorghum, and wheat) and energy crop production. Currently there is not a market for the two energy crops (switchgrass and biomass sorghum). Therefore, a breakeven price of each energy crop was determined by its production cost plus the net revenue from the next best agricultural production alternative, or land rent, whichever is higher (the *opportunity cost* of using the land for energy crop production) (Larson et al. 2015).

The street level network was applied to estimate transportation costs of biomass from the field to the facility. The hauling distance from the field to the conversion facility was calculated as the distance between the center point of the land resource unit in which feedstock is produced and the center point of the land resource unit where the conversion facility is located. The most accessible routes between land resource units and the facility were identified based on the speed limits of each type of roads following the hierarchy: 1) primary/major roads, 2) secondary roads, 3) local and rural roads, and 4) other roads. The five-axle 48-ft semi-tractor trailers were used to transport baled feedstock. The loading capacity of the flatbed trailer was assumed to carry 24 large square bales and totaled 14 dry tons per load. Transportation costs included 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 conversion facility.

It was assumed that feedstock is harvested once per year using large rectangular balers. The bales are then placed into storage at the edge of the field until transported to a conversion facility. The harvest costs consisted of machinery operating and ownership costs plus labor costs for mowing, raking, baling, and loading operations. Storage costs included the materials (tarps and wooden pallets) used to protect bales stored on the edge of field, and the labor and tractor costs for material handling and baling. Dry matter losses for storage periods of up to 365 days for the large rectangular bales were modeled using estimated losses by time in storage for switchgrass from Mooney et al. (2012). Labor costs, operating and ownership costs for equipment and vehicles, and other inputs used for energy crop supply chains were obtained from Larson et al. (2010) and the University of Tennessee Institute of Agriculture (UTIA 2011).

Traditional crop yields at the sub-county level were taken from the SSURGO database maintained by the U.S. Department of Agriculture (U.S. Department of Agriculture 2014). Areas in each traditional crop for each land resource unit were taken from the Cropland Data Layer Database (U.S. Department of Agriculture 2011). Data for traditional crop prices were for the 2010-11 crop year (U.S. Department of Agriculture 2012). Switchgrass and biomass sorghum yields were obtained from Jager et al. (2010) and U.S. Department of Energy (2011). The yields of mature switchgrass was estimated around 8.0–9.4 dry ton (dt) per acre. The yields of mature biomass sorghum after adjusting the lodging problem that causes stalks falling over during harvest ranged between 5.5 dt/acre and 12.0 dt/acre.

Step 2: Determining Truck Traffic Emissions from Feedstock Hauls

The Motor Vehicle Emissions Simulator (MOVES), an emission modeling program designed under the guidance of the U.S. EPA (U.S. EPA 2012), was used to estimate equivalent carbon dioxide (CO_2e) emissions from mobile sources. The version of the program used in this study is MOVES (2010b). MOVES is a regulatory mobile emission model that can be used to perform a quantitative estimate of project-level emission inventories (Vallamsundar and Lin 2011). MOVES can be used to simulate transportation emissions at various scales, such as individual roads and intersections at the county, region, and nationwide level. A number of recent studies have applied MOVES to estimate local or regional transportation emissions impacts of road projects or traffic management (e.g., Tao et al. 2011, Bigazzi and Figliozzi 2012, Papson et al. 2012, Xie et al. 2012, Mukherjee et al. 2013, Ghafghazi and Hatzopoulou 2014, Guo and Zhang 2014).

The following assumptions were made to facilitate the modeling of trucking emissions from feedstock transportation using MOVES. First, the *Project scale* option in MOVES was selected to permit emission modeling for individual road links. Second, the calendar year used in the model was 2010. Third, 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 reduce computational time. Deliveries typically occurred from Monday through Friday during these aforementioned months. Fourth, meteorological data in a single county were used to represent all the surrounding counties in the area. Thus, Blount, Cumberland, Davidson, and Madison counties in Tennessee were selected given the presence of a regional airport located in each county. The surface hourly temperature and humidity data for these counties were collected from the National Climatic Data Center. Finally, the combination short-haul truck option was selected since it has the tractor-trailer type vehicle configuration. Emission factors generated from the models were then used to simulate the emissions from the additional truck traffic of feedstock hauls between farms and conversion facilities in the optimal energy crop supply chains determined in Step 1.

RESULTS

Economical Efficient Feedstock Supply Chains

Table 1 presents the total cost of switchgrass and biomass sorghum for a 50-MGY conversion facility. The total cost for delivering about 658,000 tons per year of switchgrass to the least-cost site in each of the three regions ranged between $45.9 million and $47.7 million. The average cost per dry ton of switchgrass in the eastern and central regions was relatively lower, about $70, while the cost increased to more than $72 per dry ton if switchgrass was produced in the west. The harvest cost accounted for more than half of the total supply chains cost, while transportation costs were estimated at more than 20% of total cost in each region. Production cost, including the opportunity cost of land, made up around 20% of total cost in all regions.

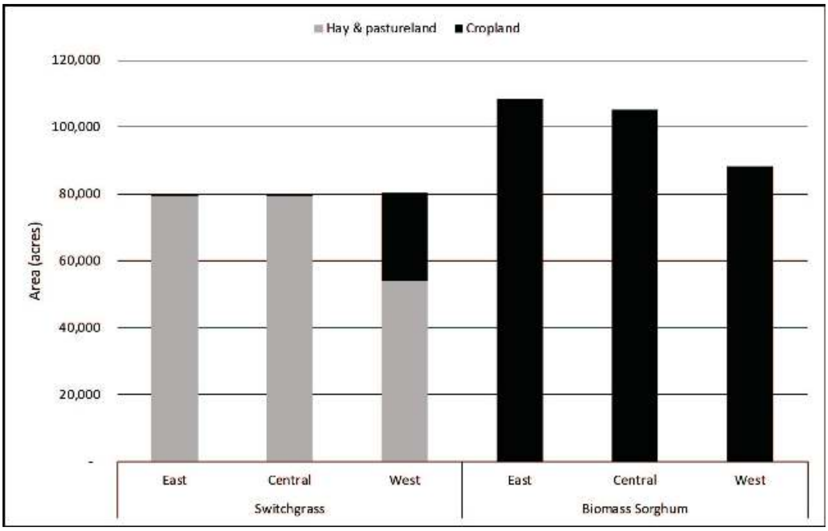
Table 1: Total Costs, Harvested Area, and Vehicle Miles Traveled (VMT) of Supplying Switchgrass and Biomass Sorghum to Conversion Facility by Region in Tennessee

	Switchgrass			Biomass Sorghum		
Region	**East**	**Central**	**West**	**East**	**Central**	**West**
Conversion Facility Location	McMinn County	Bedford County	Weakley County	Marion County	Giles County	Obion County
Total cost (million $)	**46.3**	**45.9**	**47.7**	**116.2**	**101.2**	**73.5**
Production (million $)	9.2	9.2	9.3	69.3	59.1	31.4
Harvest (million $)	23.9	23.9	24.0	28.3	27.8	25.2
Storage (million $)	3.3	3.3	3.3	3.3	3.3	3.3
Transportation (million $)	10.0	9.4	11.1	15.3	11.0	13.5
Cost per ton ($)	**70.4**	**69.7**	**72.4**	**176.7**	**153.8**	**111.7**
Total harvested area (1,000 acres)	**79.7**	**79.9**	**80.5**	**108.5**	**105.3**	**88.4**
VMT (1,000 miles)	**1,733**	**1,540**	**2,088**	**4,385**	**4,006**	**3,565**

Compared with the supply chain cost of switchgrass, biomass sorghum was a more expensive feedstock to produce in Tennessee. The total supply chain costs of biomass sorghum ranged between $73.5 million and $116.2 million across the three regions. In the eastern region, the total plant gate cost for biomass sorghum was nearly 150% higher than the cost of switchgrass using the same harvest and storage system. The feedstock costs in east Tennessee were the highest due to lower yields of biomass sorghum. In addition, the cost of hauling biomass sorghum to the conversion facility in east Tennessee was higher than for the sites in the central and western regions due to the larger draw area of biomass sorghum in east Tennessee. Land suitable for biomass sorghum production was smaller and less concentrated than in the other regions. Production costs of biomass sorghum were the highest among all costs. Unlike perennial switchgrass, biomass sorghum is an annual crop that is reestablished each year and had higher fertilizer and chemical costs that contributed to the higher production costs relative to switchgrass. Transportation cost accounted for about 11% to 18% of the total supply chain cost.

Harvested area for switchgrass in each of the three regions was similar, about 80,000 acres (see Table 1 and Figure 1). The total feedstock draw area was influenced by the yield of switchgrass in each land resource unit and the availability of lower opportunity cost of hay and pasture lands. As the opportunity cost of converting hay and pastureland to switchgrass production was the least among all crops in Tennessee, the available hay and pastureland in each land resource unit determines the density of switchgrass produced in that spatial unit. Figure 1 shows that nearly all area used for switchgrass production in east and central Tennessee were from hay and pasture lands. About one-third of harvested area was from croplands in west Tennessee given the relatively fewer acreages of hay and pasture within the region.

Figure 1: Land Use Change for Dedicated Energy Crop Production



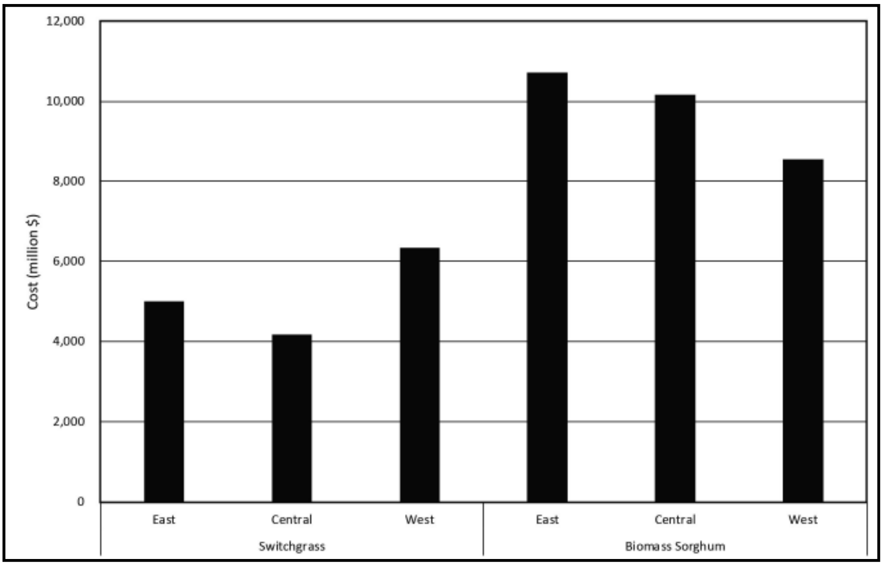
Harvested areas of biomass sorghum in east Tennessee were larger than in the central and western regions (Table 1 and Figure 1). The density of feedstock production in each land resource unit in the east region was smaller. In contrast, available crop land and yields of biomass sorghum in central and west Tennessee were higher, thus generating higher feedstock production density in land resource units and smaller feedstock draw area. Total harvested area in the eastern region reached more than 108,000 acres, while 20% less area [1 – (88.4 thousand acres / 108.5 thousand acres)] was needed for the conversion facility in west Tennessee. In addition, biomass sorghum can only be planted on crop lands, and a lack of available crop land in east Tennessee resulted in a larger area to produce biomass sorghum. The optimal locations of the conversion facilities in all three regions were close to the state's border, primarily driven by the yield of biomass sorghum and availability of croplands in land resource units.

GHG Emissions from Feedstock Transportation

Hauling switchgrass to the optimal site in west Tennessee generated the highest Vehicle Miles Traveled (VMT), over 2.0 million miles (Table 1). About 1.5 million miles were traveled for feedstock deliveries to the conversion facility in central Tennessee. Fewer truck emissions were produced than the selected sites in the other two regions given the smaller feedstock draw area and VMT (Figure 2). In contrast, VMTs were much higher for switchgrass in the western region due to a smaller availability of less expensive hay and pasture lands in the region. This region produced the most emissions from feedstock transportation, about 6,350 tons of CO_2e annually. For biomass sorghum, the VMT to the conversion facility in east Tennessee was the highest (Table 1), followed by the facility in the central region. Given the higher density of crop lands located in west Tennessee, the VMT of biomass sorghum to the conversion facility was the lowest among three regions, over

3.5 million miles. Feedstock transportation emissions of CO_2e of more than 8,500 tons per year were estimated for the region.

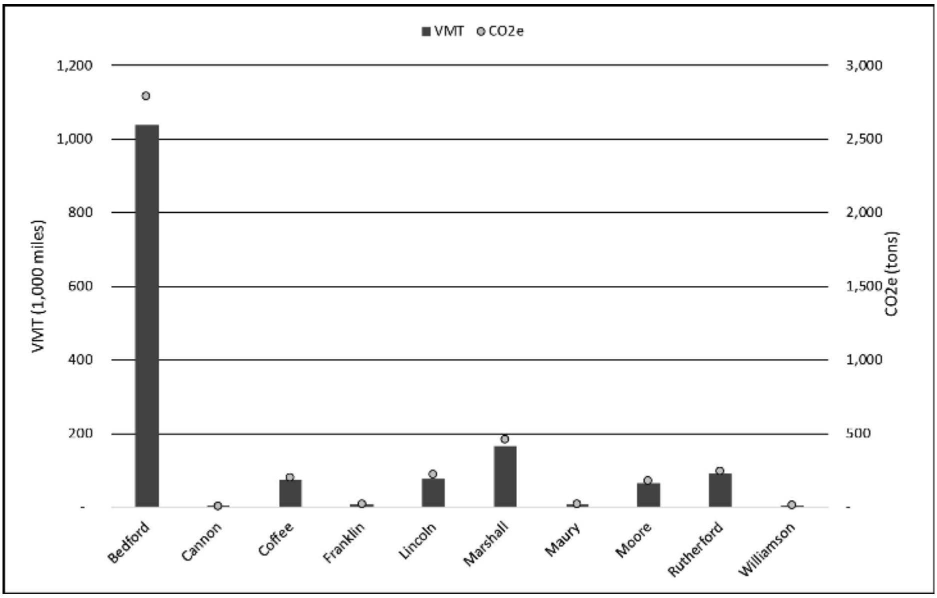
Figure 2: Transportation Emissions (CO2e) of Energy Crops to the Conversion Facility by Region in Tennessee



The summary of supply chain costs and CO_2e emissions of feedstock transportation by region in Table 1 and Figure 2 shows that switchgrass-based biofuels have much lower feedstock cost compared with biomass sorghum. Similarly, the emissions generated from hauling biomass sorghum to the conversion facility were much higher than that associated with transporting switchgrass due to the more dispersed feedstock draw area and the supply location of feedstock. Although the differences in the supply chains' cost of switchgrass among all three regions were small, the emissions produced from delivering feedstock to the conversion facility in the central region were clearly lower than the other two regions. Thus, the conversion facility using switchgrass as feedstock located in central Tennessee was found to be the most sustainable with the least economic costs and hauling emissions of feedstock.

The least cost location for a switchgrass biofuel plant was Bedford County in central Tennessee (see Table 1 and Figure 2). VMT and transportation emissions related to transport of switchgrass to the facility in the related counties are presented in Figure 3. With the facility located in Bedford County, more than 1.0 million trucking miles were expected due to feedstock delivery and resulted in nearly 2,800 tons of CO_2e per year within the county. Additional traffic was also incurred in the surrounding counties (e.g., Marshall County, Coffee County, Rutherford County, and Moore County) and produced about 200 tons of CO_2e annually in these counties.

Figure 3: VMT and CO_2e of Switchgrass Transportation to the Conversion Facility in Related Counties in Central Tennessee



CONCLUSIONS

Driven by the increasing interests in the development of advanced biofuel in the U.S., the efficiency of the supply chains providing biomass feedstock to biorefineries is under scrutiny. In addition, the potential environmental impacts of feedstock transportation have generated increased attention given the potential increases in traffic on the current road system. This study estimates the supply chains' cost and hauling emissions of two feedstocks (switchgrass and biomass sorghum) in east, central, and west Tennessee. A spatially-oriented mathematical programming model utilizing crop and pasture land availability, yield, the real road network, and other data was used to determine the optimal location of a single-feedstock 50-MGY conversion facility, associated feedstock draw area, and delivery routes on the road network. Based on the output of the cost minimization from the model, the emissions of additional traffic from feedstock transportation in each region is simulated using the U.S. EPA's emissions modeling tool.

Our results indicate that the cost of biomass feedstock supply chains is influenced by the yield of the feedstock, available crop land, and opportunity cost of converting traditional crops to energy crops. From an economic standpoint, switchgrass is found to be more feasible than biomass sorghum for cellulosic biofuel production in Tennessee. Significantly higher supply chain costs of biomass sorghum are primarily driven by its production cost. The inputs required to produce an annual crop (biomass sorghum) are more than for a perennial grass (switchgrass). Furthermore, limited availability of crop land and less fertile soil, particularly in east Tennessee, generate a more dispersed feedstock draw area and higher transportation cost.

Additional truck traffic from biomass feedstock hauling produces more emissions in the study region. Comparing trucking emissions, hauling biomass sorghum to the conversion facility created significantly more GHG emissions than delivering switchgrass. The higher emission level was related to substantial vehicle travel miles associated with biomass sorghum deliveries resulting from the larger feedstock draw area. Hauling switchgrass to the optimal site in central Tennessee produces the least emissions. Our findings, in line with Jäppinen et al. (2013), suggest that availability of land types and the geographically diverse landscape across the state are influential to the supply chains' cost and feedstock transportation emissions for biomass feedstock. Thus, spatial characteristics will be important elements when designing a commercial-scale bioenergy sector in the regional development plan.

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APPENDIX

The cost of energy crops at the conversion facility gate is defined as:

(1) $TC_F = C_{opportunity} + C_{production} + C_{harvest} + C_{storage} + C_{transportation}$

where TC_F is the total economic cost (\$) of the biomass supply chain, and $C_{opportunity}$, $C_{production}$, $C_{harvest}$, $C_{storage}$, and $C_{transportation}$ are opportunity costs from land conversion, production cost, harvest cost, storage cost, and transportation cost of energy crops, respectively. Table A1 summarizes the definition of the parameters and variables used in the equations.

The opportunity cost for energy crops (either switchgrass or biomass sorghum) production is defined as the profit of previous crop in equation (2). If the net revenue of previous crop is less than the county-level land rent, the land rent is used as the opportunity cost instead. The production cost in equation (3) comprise both amortized establishment cost of the first year and an annual maintenance cost. Harvest cost factor (Sigma) in equation (4) includes equipment ownership cost, operating cost, operating interest cost, and labor cost. Similarly, cost of storage material, equipment ownership, storage operation, operating interest, and labor are considered in the storage cost factor (γ) in equation (5). The transportation cost factor, θ, in equation (6) considers loading and unloading costs, labor costs, and machinery costs.

(2) $$C_{opportunity} = \begin{cases} \sum_{ip}\left(\frac{Price_{ip} * Yield_{ip} - PC_{ip}}{Yield_i^{swi}} * XC_{ip}\right), \text{if } (Price_{ip} * Yield_{ip} - PC_{ip}) - LR_{ip} \geq 0 \\ \sum_{ip}\left(\frac{LR_{ip}}{Yield_i^{swi}} * XC_{ip}\right), \quad \text{if } (Price_{ip} * Yield_{ip} - PC_{ip}) - LR_{ip} < 0 \end{cases}$$

(3) $C_{production} = \sum_{ip}\left(\frac{\text{Est+AM}}{Yield_i^{swi}} * XC_{ip}\right)$

(4) $C_{harvest} = \sum_{ip}\left(\frac{\text{Sigma}_i}{Yield_i^{swi}} \times XC_{ip}\right)$

(5) $C_{storage} = \sum_{mipt} \gamma_{it} * NXS_{mipt}$

(6) $C_{transportation} = \sum_i \theta_i \times \frac{\sum_{mp} XTN_{mip} + \sum_{mpt} XTO_{mipt}}{1-DMLT}$

Subject to:

Land use constraints:

(7) $A_{ip} \leq PAS_p \times aa_{ip}, \forall\, i, p$

(8) $XC_{ip} \leq Yield_i^{swi} \times A_{ip}, \forall\, i, p$

Harvest constraints:

(9) $XC_{ip} - \sum_m XH_{mip} \geq 0, \quad \forall\, i, p$

(10) $\sum_{i,p,} XH_{mip} = \frac{CapUnit}{\lambda} \times rateava_m, Dec \leq m \leq Feb\ \&\ \forall\, m$

(11) $XH_{mip} = 0, \ March \leq m \leq Oct\ \forall\, m, i, p$

(12) $Numb_m{}^{\kappa} \times avehour_m - \sum_{i,p}(mtb_i{}^{\kappa} \times AH_{mip}) \geq 0\ ,\ \forall\, m$

Harvest-inventory balance constraints:

(13) $\sum_t^2 NXS_{mipt} = XH_{mi} - \frac{XTN_{mip}}{1-DMLT}\ ,\ Nov\ \leq m \leq Feb\ \&\ \forall\, m, i, p$

(14) $XS_{(m+1)ipt} = (1 - DMLS_{mt}) \times XS_{mipt} +\ NXS_{(m+1)ipt}\ ,\ Nov\ \leq m \leq Feb\ \&\ \forall\, m, i, p, t$

(15) $XS_{(m+1)ipt} = (1 - DMLS_{mt}) \times XS_{mipt} - \frac{XTO_{(m+1)ipt}}{1-DMLT},\ Mar \leq m \leq Oct\ \forall\, m, i, p, t$

(16) $XS_{mipt} = 0\ ,\ m = Oct\ \&\ \forall\, m, i, p, t$

Demand constraints

(17) $\lambda(\sum_{i,p} XTN_{mip} + \sum_{i,p,t} XTO_{mipt}) = Dd_m\ ,\ \forall\, m$

Table A1. Definitions of Subscripts, Parameters and Variables

	Unit	Definition
Subscripts		
i		locations of energy crop production field
m		month
p		crops (hay & pasture, corn, soybean, wheat)
t		storage protection method
k		type of machinery (tractor, mower, loader, rake)
Parameters		
Price_{ip}	$/unit	traditional crop price
Yield_{ip}	acre/unit	tradition crop yield
PC_{ip}	$/acre	production cost of traditional crop
$Yield_i^{swi}$	d ton/acre	yield for energy crop in each hexagon
LR_{ip}	$/acre	land rent of traditional crop
Est	$/acre	Establishment cost in the first year
AM	$/acre	Annual maintenance cost
Sigma_i	$/acre	cost of harvesting energy crop
γ_{it}	$/d ton	cost of storing energy crop
θ_i	$/d ton	cost of transporting energy crop from field to facility
aa_{ip}	acre	cropland available in each hexagon for each crop
CapUnit	gallon/year	annual capacity of a conversion facility
λ	gallon/d ton	energy crop-ethanol conversional rate
$rateava_m$	%	ratio of working hours in each month to total
$avehour_m$	hour	average working hours of machinery in each month
mtb_i	hour/acre	machine time per acre for each machinery
PAS_p	%	maximum percent of land converted
DMLT	%	dry matter loss during transportation
$DMLS_{mt}$	%	dry matter loss during storage
Dd_m	gallon/month	monthly demand for ethanol
Variables		
A	acre	ha of energy crop produced annually
AH	acre	ha of energy crop harvested monthly
XC	d ton	dry weight of energy crop produced annually
XH	d ton	dry weight of energy crop harvested monthly
XTN	d ton	dry weight of energy crop transported directly to the facility after harvest
NXS	d ton	dry weight of energy crop newly stored monthly from November to February
XS	d ton	dry weight of energy crop stored monthly from November to October
XTO	d ton	dry weight of energy crop transported from storage to the facility
Numb	unit	number of equipment used in harvest

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