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Analyzing Economic and Environmental Performance of Switchgrass Biofuel Supply Chains

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Abstract This study optimized the net present value (NPV) of profit of various switchgrass-based ethanol supply chains and estimated associated greenhouse gas (GHG) emissions in west Tennessee. Three configurations of feedstock harvesting and storage, including a large round baler system, a large square baler system, and a chopping/densification system, were evaluated. A mixed-integer mathematical programming model incorporating high-resolution spatial data was used to determine the optimal locations and capacities of cellulosic ethanol plants and feedstock preprocessing facilities, and associated feedstock-draw areas by maximizing the NPV of profit over 20 years. The optimized outputs were then used to estimate the GHG emissions produced in the biofuel supply chain (BSC) per year. The study shows that BSC configurations have important implications for the economic and environmental performance of the system. The harvest and storage configurations affect the locations of conversion and preprocessing facilities, and associated feedstock-draw areas, hence impacting the cost and emissions of both feedstock and biofuels transportation. The findings suggest the BSC system that harvests feedstock with forage choppers and utilizes stretch-wrap balers to increase feedstock density has the highest NPV of profit. The BSC system that uses large square balers for harvest and storage emits the lowest amount of GHGs per year. In addition, the sensitivity analysis suggests that biofuel price and scaling factor of facility capital was influential to the economics of BSC systems. The breakeven price of biofuel for the three BSCs was around \$0.97 L^{-1}.

Keywords Cellulosic ethanol · Switchgrass · Supply chains · Net present value · GHG emissions

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Introduction

Driven by the biofuel mandates established in the Energy Independence and Security Act (EISA) of 2007 [1], the development of a commercialized cellulosic biofuel industry from lignocellulosic biomass (LCB) feedstock has become one of the major goals of US national energy policy [2]. Compared with first generation feedstock such as corn, LCB crops typically have higher biofuel yields per unit of land, less demand for water and fertilizers, and are not directly linked to the price of food crops. However, the lack of efficiency in the cellulosic biofuel supply chain (BSC) has become a critical issue that hinders cellulosic biofuel from becoming economically feasible for large-scale commercialization [3, 4]. Therefore, it is important to determine how a BSC that consists of the upstream (i.e., LCB production, collection, storage, and transportation), midstream (biofuel conversion), and downstream (biofuel delivery to blending sites or distribution center) activities should be optimally configured to increase the profit of cellulosic biofuel production.

In addition to the economic efficiency of the BSC, the US Environmental Protection Agency (EPA) requires that life cycle greenhouse gas (GHG) emissions of cellulosic biofuels be 60 % lower than fossil fuel emissions [1]. As expansion of the biofuel and biopower industry occurs and biogenic GHG emissions increase, more rigorous GHG regulations on the bioenergy industry by environmental groups can be expected. To mitigate the increasing concerns about allowable life cycle

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GHG emissions related to bioenergy production, research considering GHG emissions produced in the cellulosic BSC is crucial. GHG emissions generated from land use change and activities related to feedstock and biofuel management in the BSC could impact the sustainability of the LCB-based biofuel industry [5]. Thus, knowledge about the impacts of alternative BSC configurations on GHG emissions is vital to the long-term development of a cellulosic biofuel industry.

The literature on an economical efficient LCB-BSC configuration has quickly expanded over the past decade. A good summary of the BSC system boundaries and related analytical methods can be found in An et al. [3], de Meyer et al. [4], and Sharma et al. [6]. Existing studies have examined the impact on feedstock cost of the optimal configuration of upstream activities within a BSC. For instance, Kuman and Sokhansanj [7] evaluated three biomass collection systems (baling, loafing, and ensiling) and compared seven cases in terms of feedstock cost, energy use, and GHG emissions from the field to the biorefinery plant gate. Sokhansanj et al. [8] evaluated various densification options and transportation modes in large-scale production, harvest, and logistics of switchgrass. The cost of feedstock and energy input in the production and logistics systems were compared across different feedstock yields and biorefinery capacities. The impact of potential technologies on logistics cost reductions was also estimated. Larson et al. [9] applied an enterprise budgeting approach to evaluate the cost of three feedstock harvest and storage methods. The delivered feedstock cost was estimated for two traditional agricultural baler methods and a potential chopping/densification technology in a feedstock supply chain to serve a potential commercial-scale conversion facility. More recently, Zhang et al. [10] included two traditional agricultural baler systems and one chopping/pelletizing technology in an integrated BSC to determine the optimal configuration. The locations and capacities of biorefineries and preprocessing facilities were determined. In addition to economic outcomes, GHG emissions incurred in the BSC systems have received recent attention (e.g., [7, 11–13]).

The aforementioned studies have offered useful insight into the impact of alternative BSC configurations on LCB feedstock cost; however, most studies only considered the biomass feedstock supply chain. Also, the influence of the spatial attributes of a region for the optimal placement and configuration of a BSC was generally overlooked or evaluated only at a large spatial scale, such as at the county level. The optimal configuration of the BSC is closely related to regional attributes because available land resources for growing feedstock and the road network for hauling feedstock and biofuel products affect the location decision of conversion and preprocessing facilities, and feedstock-draw areas [14]. In addition, GHG emissions in the BSC may be influenced by local geographical conditions [15].

This study optimized and compared the net present value (NPV) of profit associated with three feedstock harvest and storage configurations in the BSC presented in Larson et al. [9] using high-resolution spatial data. The GHG emissions of optimized cellulosic BSC were also estimated and examined among the evaluated systems. In addition, the optimal placement and sizes of conversion facilities and feedstock-draw areas were determined. Switchgrass in Tennessee was used as a case study given the suitability of switchgrass in the southeastern region [16]. Cellulosic ethanol was the considered biofuel in the present study given the recent development of conversion technology [17].

Modeling Biofuel Supply Chains

Biofuel Supply Chain Configurations

The components of the BSC in this study included feedstock establishment, production, harvest, preprocessing, storage, transportation, and biofuel conversion and transportation. The definitions of the three feedstock harvest and storage configurations studied by Larson et al. [9] are the following:

- System (a): switchgrass feedstock was grown considering the competition with other crops for land. Matured feedstock was harvested with large round agricultural balers. Large round bales were stored on the side of the field without covers and brought to conversion facilities using semi-trailers. Conversion facilities reduced the size of the switchgrass (~243.84 cm) to powder by a hammermill. Biofuels were then transported to the blending site for distribution.
- System (b): the design is similar to BSC (a) except using a large square baler for harvesting feedstock. Outdoor-stored large square bales were then protected with tarp and pallet to reduce dry-matter loss.
- System (c): Switchgrass competed with other crops for land and was harvested by a forage chopper in a single pass. Chopped feedstock was preprocessed with a stretch-wrap baler to form higher weight, higher density round bales [9]. The densified wrapped bales were stored at the preprocessing site and delivered to conversion facilities each month. Conversion facilities reduced the size of chopped switchgrass (~2.54 cm) to powder by a hammermill. Biofuels were then transported to the blending site for distribution.

Figure 1 presents the sequence of operations from field to conversion facilities, including feedstock harvest, storage, and transportation, for the three systems. It is apparent that more steps were involved under BSC (c) compared to the other two systems due to the feedstock preprocessing (densification)

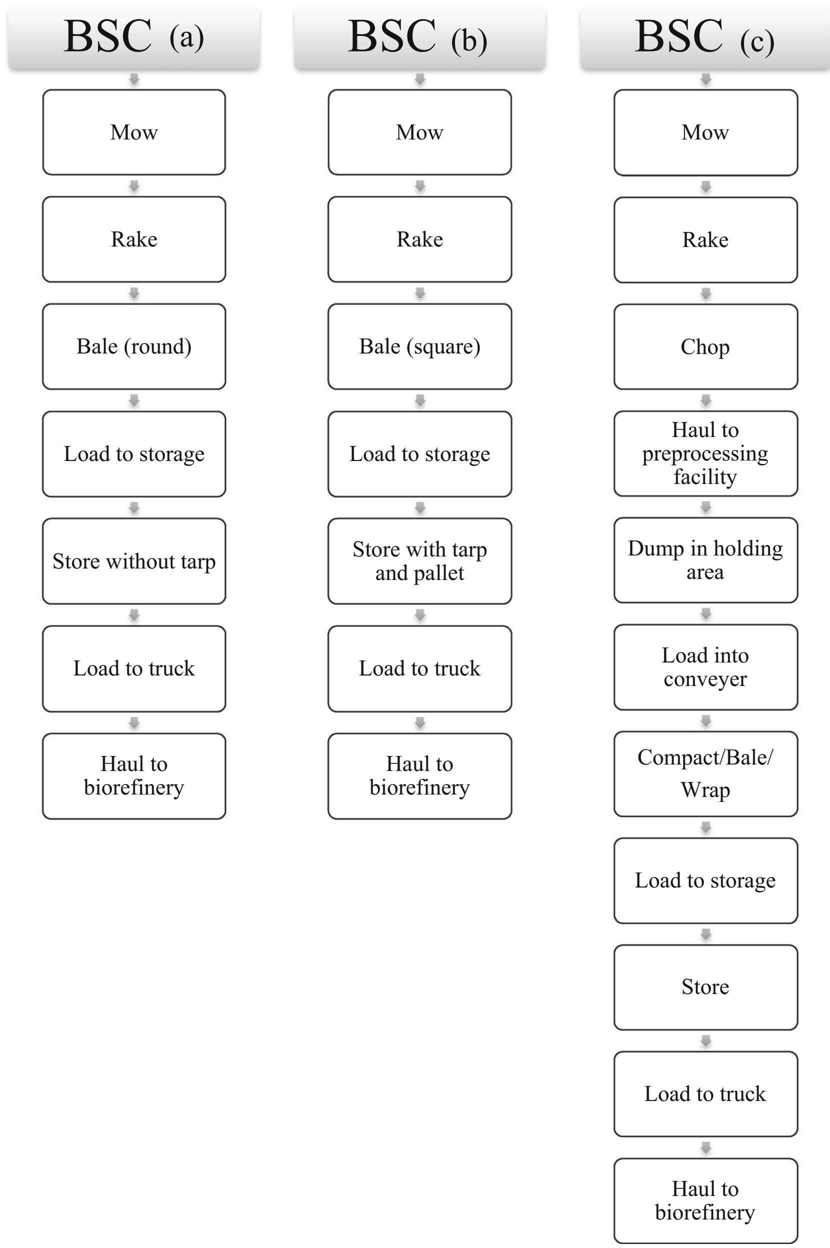


Fig 1 Switchgrass supply chain from field to conversion facilities. BSC (**a**): large round balers; BSC (**b**): large square balers; BSC (**c**): choppers and stretch-wrap balers

process. After feedstock was delivered to conversion facilities, the sequential steps were assumed identical among all systems, including feedstock grinding, biofuel production, and biofuel transportation to the blending site.

For all three systems, the feedstock was assumed harvested once per year extending from November through February. The harvest started after senescence, typically in late October, to minimize the harvest of nutrients in switchgrass and maximize its yield [9, 18]. Feedstock harvest was completed by February to prevent hampering the yield of new switchgrass that typically germinates in early March. For each system, harvested feedstock used for biofuel production in the harvest season was assumed to be delivered directly from the farm to conversion facilities without being stored or preprocessed. Only feedstock used for producing biofuel during the off-harvest season was assumed to require storage and/or preprocessing. Storage dry-matter losses of feedstock in each system in Tennessee were incorporated based on Mooney et al. [19]. All farming equipment and preprocessing facilities in the BSC were assumed to be dedicated for producing feedstock in the harvest season. The equipment could be owned, managed, and coordinated by conversion facilities or the entity contracted with the conversion facilities. Demand for cellulosic ethanol at the blending site was assumed to be deterministic and the conversion rate from feedstock to cellulosic ethanol was constant.

Overview of the Model

Figure 2 depicts an overview of the modeling framework. Detailed spatial data were used as an input for a spatially oriented, mixed-integer mathematical programming model developed in Yu et al. [20]. The objective of the model is to maximize the NPV of cash flow in each BSC system, subject to constraints on feedstock production availability, the demand for feedstock by the conversion facility, and the mass balance of inflows and outflows in the system. The balance of monthly inventory and delivery of feedstock was maintained to assure sufficient feedstock supply for each conversion facility. The model considered the potential availability of biomass and biofuel demand in the study area to determine the optimal locations and production/processing levels of the conversion and preprocessing facilities.

The potential draw area for feedstock production was based on remote sensing data, disaggregated into a vector database of contiguous 13 km^2 land resource units. The price to entice land owners to convert land from current use to switchgrass production included the production cost of switchgrass *plus* the foregone profit of the net revenue from the next best production alternative or land rent, whichever was larger (i.e., *opportunity cost* of land) [20]. Both switchgrass production cost and the opportunity cost of land were considered in the price since a price considerably greater than the cash rental rate would be required to attract land owners to convert land for switchgrass due to the lost option value [21]. The *opportunity cost* (*OC*) of converting cropland or pastureland for switchgrass was calculated in Eq. (1):

$$OC = \begin{cases} \sum_{icb}\left(\frac{P_{ic}\times Y_{ic}-C_{ic}}{y_{ib}}\times X_{icb}\right), & \text{if}\left(P_{ic}\times Y_{ic}-C_{ic}\geq R_{ic}\right) \\ \sum_{ic}\left(\frac{L_{ic}}{y_{ib}}\times X_{icb}\right), & \text{if}\left(P_{ic}\times Y_{ic}-PC_{ic}>R_{ic}\right) \end{cases} \quad (1)$$

where P_{ic}, Y_{ic}, C_{ic}, and R_{ic} was price, yield, production cost, and land rent for traditional crop *c* in land resource unit *i*. y_{ib} was the yield of switchgrass and X_{icb} was the amount of switchgrass produced from converting the land in resource unit *i* from traditional field crop *c* using switchgrass harvesting method *b* (i.e., baling or chopping).

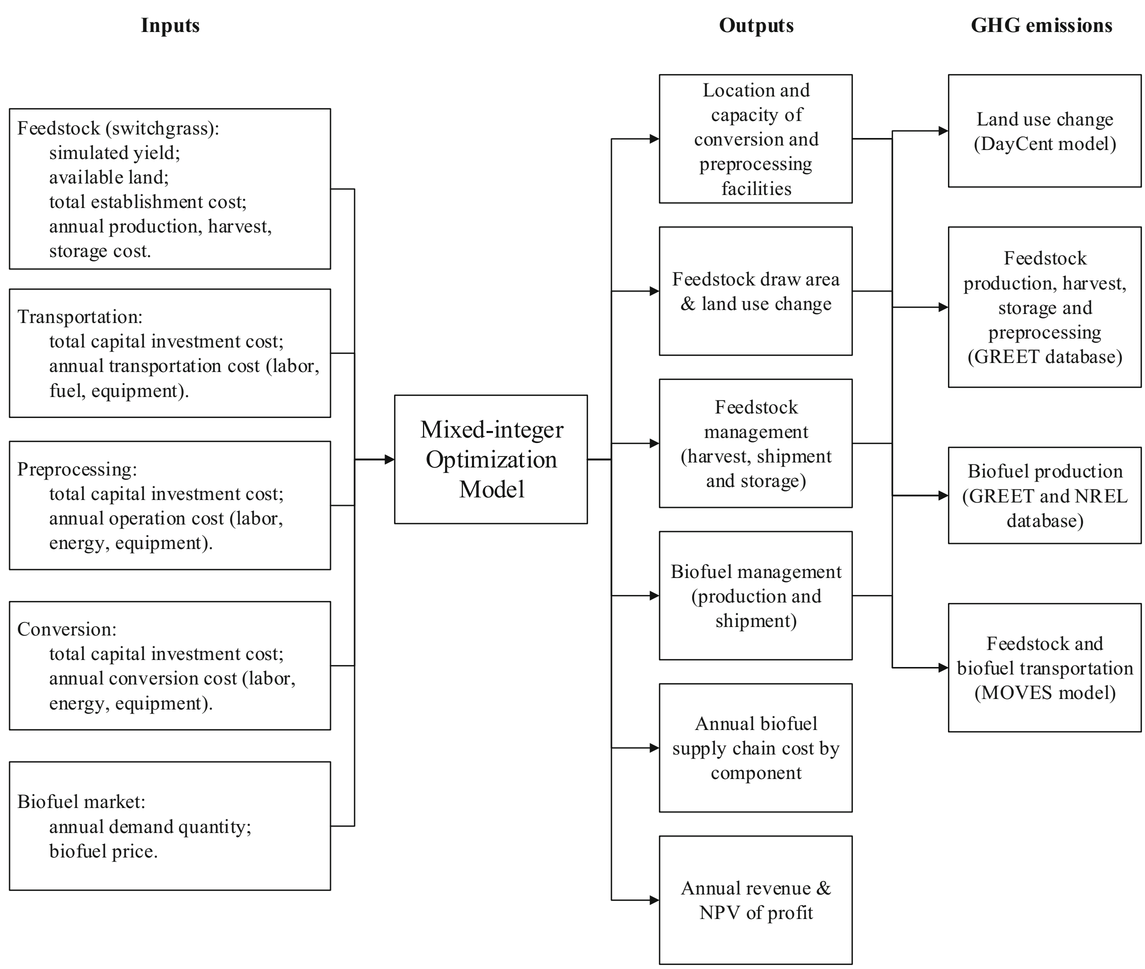


Fig 2 Components of the spatially oriented optimization model

The simulated switchgrass yields [22] and cropland/pastureland information [23] were used to estimate feedstock production in each land resource unit. Traditional crop yields were from the SSURGO database at the sub-county level [24]. The data for traditional crop prices used in the model were averages for 2010–2012 [25]. The land rent by county for cropland and pastureland were based on Tennessee cash rents in 2011–12 from USDA NASS [26]. In addition, the establishment cost of feedstock at year 0 and the cost of reseeding feedstock at the end of year 10 were included to account for two switchgrass production cycles. Salvage value of the switchgrass stand at the end of year 10 was assumed to be zero. Annual costs of feedstock maintenance and storage [27] were also considered.

To determine transportation cost, the hauling distance of the feedstock and biofuel was calculated based on street-level network data [28]. 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 road was used when generating the routes between origins and destinations to determine the most accessible and efficient routes. Annual transportation costs included labor, operating, and ownership costs of tractors with front-end loaders used for loading and unloading of bales. The travel time for feedstock and biofuel transportation was calculated using hauling distances and speed limits on routes determined from the real street network. The annual cost of transportation was then determined based on the cost of equipment, labor/driver, and fuel use given the travel time. The investment costs of trucks with trailers or oil tankers used for transporting feedstock or biofuels were also counted.

The one-time capital investment cost of preprocessing facilities and the annual operating cost of preprocessing, including labor, energy, and equipment, were from Larson et al. [9]. The throughput of the stretch-wrap baler was 44.64 metric tons (Mg) per hour. Three capacities of the stretch-wrap baler, including 62,832, 125,663, and 188,495 Mg, were considered. A scaling factor of 0.7 was assumed to reflect economies of scale in capital investment costs and salvage values for larger capacities [29]. For conversion facilities, the capital investment and annual operating costs were generated from National Renewable Energy Laboratory [17]. The cost of feedstock size reduction in the conversion facilities was based on Kumar and Sokhansanj [7]. Two capacities, 380 and 190 million liters per year (MLY), were considered for the conversion facilities [10]. Similar to preprocessing facilities, a scaling factor of 0.7 was used to capture economies of scale in larger conversion facilities. The conversion technology was assumed to have a biofuel yield of 317 L from 1 Mg of switchgrass [30]. Preprocessing and conversion facilities were designed to be located in available industrial parks with access to required infrastructure. Not more than one conversion facility of any capacity could be located at a potential industrial park.

The NPV of the profit for each BSC system was calculated assuming a discount rate of 0.15 for a 20-year period. West Tennessee was selected as the study area because it is the largest agricultural production area in the state. A blending site adjacent to Memphis, the second largest metropolitan area in the state, is currently located in this region to meet the local high demand for transportation fuels. In 2011, about 628 trillion Btu (~19 billion L) of energy (primarily petroleum) were used by the transportation sector in Tennessee [31]. Given the region's population share within the state (~28 %), its transportation fuel consumption was estimated to be around 5.3 billion L. Assuming replacing 20 % of estimated transportation fuel consumption in the region with cellulosic ethanol, the annual demand in the study area would be around 1.1 billion L. The biofuel price, including the cost of the Renewable Identification Number (RIN), was projected at $1.14 per liter at the blending site [32].

Maximizing NPV for a BSC system determined the optimal locations of conversion facilities, locations of preprocessing facilities (if available in the system), feedstock-draw areas, and monthly management of feedstock and biofuel (i.e., delivery and storage) for that particular BSC. Annual total revenue and fixed and variable costs by BSC component were generated. The BSC outputs became the inputs for the ex-post estimation of GHG emissions for each BSC system. The feedstock production area converted from previous agricultural activities in a land resource unit was used in a biogeochemical model, DayCent model [33], to simulate GHG emissions from land use change. After land conversion was estimated, the DayCent model considered soil properties, crop types, and local weather in estimating the net change of GHG emissions in a steady-state status over the study period. The emission factors in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model 2013 [34] were used to calculate GHG emissions from machinery combustion in feedstock production, harvest, and storage. Diesel consumption was calculated as the time used during each operation (hours/hectare) multiplied by the fuel used (liters/hour) by the tractor. The GHG emissions from electricity used in the preprocessing and conversion facilities were calculated based on the fossil fuel sources used to produce electricity (e.g., coal, natural gas) in Tennessee in 2011 [35] and associated emission factors in Intergovernmental Panel on Climate Change [36]. The consumption of gasoline and electricity for the biofuel conversion technology used in the current study was obtained from Hsu et al. [37].

The US Environmental Protection Agency's (EPA) Motor Vehicle Emissions Simulator (MOVES) was used to estimate GHG emissions and air pollutions from the trucks used in this study for transportation [38]. The version of MOVES was MOVES2010b. The air pollutants modeled were oxides of nitrogen (NO_x) and primary particulate matter less than 2.5 μm ($PM_{2.5}$) and particulate matter less than 10 μm in aerodynamic diameter (PM_{10}). 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).

To estimate truck emissions from feedstock hauling, emission rate (look-up) tables were created using the *project level scale* in MOVES. A matrix of parameters containing road (link) and meteorological conditions was created for input into the model. The range of average vehicle speeds along the link was 16 to 113 km per hour (10 to 70 mph) at increments of 16 km per hour (10 mph); the range of average road grades was −8 to +8 % at increments of 0.5 %. Each link length was 16 km (10 miles) long. To account for meteorological conditions, a range of temperatures between 40 and 90° Fahrenheit (F) were selected in 5° increments. Relative humidity of 68 % was used throughout. The combination short-haul truck was selected as the link source type, which is equivalent to the semi-trailer truck, and the single unit short-haul truck was used for tandem-axle vehicles. The MOVES model was run for the calendar year 2011 using the rural restricted access road type. This road type captures emissions as may occur on rural freeways and interstates which have a restricted vehicle access via ramps.[1]

As the biofuel price is critical behind the NPV of the BSC, a sensitivity analysis was made to examine the effect of changing net biofuel price (fuel price plus RIN) on the NPV for the three systems. Three net biofuel prices, \$0.80 L^{-1} (30 % lower than base price), \$0.97 L^{-1} (15 % lower than base price), and \$1.31 L^{-1} (15 % higher than base price), along with the base biofuel price (\$1.14 L), were considered in the analysis to reflect the wide variation of general gasoline prices and the RIN prices in west Tennessee and the nation over the past 5 years. In addition, a sensitivity analysis was performed to evaluate the responses of NPV of profit to changes in the scaling factor of investment. Selection of larger size facilities are not always more profitable over the smaller capacity in the development of biofuel industry due to the trade-off between economics of scale in plant investment cost and diseconomies of scale regarding biomass supply cost [39]. The base scaling factor used in the analysis was 0.7. To evaluate if the selection of facility capacity changes under different economies of scale in investment cost, two facility capital scaling factors (0.5 and 0.9) considered in Kocoloski et al. [40] were used in the sensitivity analysis.

[1] It should be noted, however, that the model is not overly sensitive to road type at the project level scale.

Results

The annual revenues, costs, NPV of profit, and land use changes for switchgrass production in the three BSCs are presented in Table 1. The optimized NPV of profit over 20 years for the system with loose-chopped feedstock preprocessed by a stretch-wrap baler [system (c)] was the highest among the three systems at \$1241 million. The NPV of the large square baler system [system (b)] over 20 years was estimated to be nearly \$1122 million while the large round baler system [system (a)] had the lowest NPV of profit at \$1009 million. The annual revenue stream was identical for the three BSC systems because annual demand for biofuel was predetermined. With a projected price of \$1.14 L^{-1}, the conversion facilities in aggregate have an annual revenue stream of \$1247 million, including the value of the electricity co-product.

The costs of operation varied among the three BSC systems, primarily attributed to the feedstock harvest and storage cost, and the transportation cost of feedstock and biofuels. When using the traditional agricultural baler in systems (a) and (b), the annual cost of harvesting (including mowing, raking, and baling) and storing feedstock was about \$137 million. However, using the single-pass forage chopper in system (c), the cost of harvesting was about \$46 million per year. The loose-chopped feedstock needed to be preprocessed for storage so an additional \$61 million was added to the system. Feedstock transportation cost in system (b) was the lowest because of the size advantage of the large square bales over the large round bales in system (a). For system (c), although the transportation cost of the wrapped bales with higher density was lower, the transportation of loose-chopped feedstock from the field to preprocessing sites and conversion facilities was still costly. Thus, the annual total feedstock transportation cost in system (c) was actually the highest, reaching \$91 million. The loose-chopped feedstock in system (c) had smaller feedstock size reduction cost, i.e., the grinding cost, at the conversion facilities when compared to other two systems (\$47 million vs \$79 million per year).

Three conversion facilities, all with a capacity of 380 million L, were selected in all three systems to meet the regional demand of 1.1 billion L annually. In this study, the economies of scale associated with the capital investment for the larger capacity (380 vs. 190 million L) outweighed the increases in feedstock transportation cost resulting from expanding the feedstock-draw area. The investment cost for conversion facilities was more than \$2 billion with a salvage value of \$213 million after 20 years. For system (c), \$76 million were

Table 1 NPV of profit, cost, and land use in evaluated biofuel supply chains (BSC)

	Unit	Biofuel supply chain		
		(a)	(b)	(c)
Annual sales revenue from ethanol	Million $	1218	1218	1218
Annual byproducts from biorefinery	Million $	29	29	29
Total annual revenue	Million $	1247	1247	1247
Annual feedstock opportunity costs	Million $	38	38	38
Annual feedstock maintenance cost	Million $	21	21	22
Annual feedstock harvest and storage cost	Million $	137	136	46
Annual feedstock preprocessing and storage cost	Million $	–	–	61
Annual feedstock transportation cost	Million $	79	61	91
Annual feedstock grinding cost	Million $	79	79	47
Annual biofuel production costs	Million $	362	362	362
Annual biofuel transportation cost	Million $	18	18	16
Total annual cost	Million $	733	715	682
Feedstock establishment cost (years 0 and 10)	Million $	188	188	196
Preprocessing facility investment cost (year 0)	Million $	–	–	76
Preprocessing facility salvage at year 20	Million $	–	–	8
Conversion facility investment cost (year 0)	Million $	2038	2038	2038
Conversion facility salvage at year 20	Million $	213	213	213
NPV of profit over 20 years	Million $	1009	1122	1241
Total harvest area	1000 ha	179	179	181
Cropland	1000 ha	91	93	91
Hay and pasture land	1000 ha	88	87	90
Average feedstock cost prior to grinding at biorefineries	$/Mg	88	82	87
Average feedstock cost after grinding at biorefineries	$/Mg	110	105	101

BSC (a): large round balers; BSC (b): large square balers; BSC (c): choppers and stretch-wrap balers

Salvage value of the switchgrass stand at the end of year 10 was assumed to be zero

allocated for 15 preprocessing facilities, each with a capacity of 188,495 Mg since its economies of scale in capital investment dominated the additional transportation cost of the loose-chopped material.

In systems (a) and (b), about 179,000 ha of cropland were converted to switchgrass production, while about 181,000 ha of agricultural land were utilized. The average feedstock cost at the gate of conversion facilities prior to grinding were $88, $82, and $87 Mg^{-1} for systems (a), (b), and (c), respectively, with the large square baler system [system (b)] as the most economic BSC system. The stretch-wrap baler system [system (c)] became the most efficient BSC (average feedstock cost of $101 Mg^{-1}) among the three systems when particle size reduction cost (i.e., grinding) at site was considered. The large round bale system [system (a)] was still the least efficient one with the highest feedstock cost of $110 Mg^{-1} after grinding. Given diverse assumptions and technologies considered in feedstock supply chain, previous studies of switchgrass cost at the plant gate of biorefineries presented a wide range of estimates. For instance, the estimated average cost of switchgrass per Mg at plant gate was $54.91–$64.79 by Haque et al. [41], $71.06–$80.64 by Sokhansanj et al. [8], $75.8–$92.2 by Daystar et al. [12], $98.19 by Khanna et al. [42], and $127.67–$137.87 by Kaliyan et al. [11]. The average cost of switchgrass in the present study falls in the range of the estimates in the aforementioned studies.

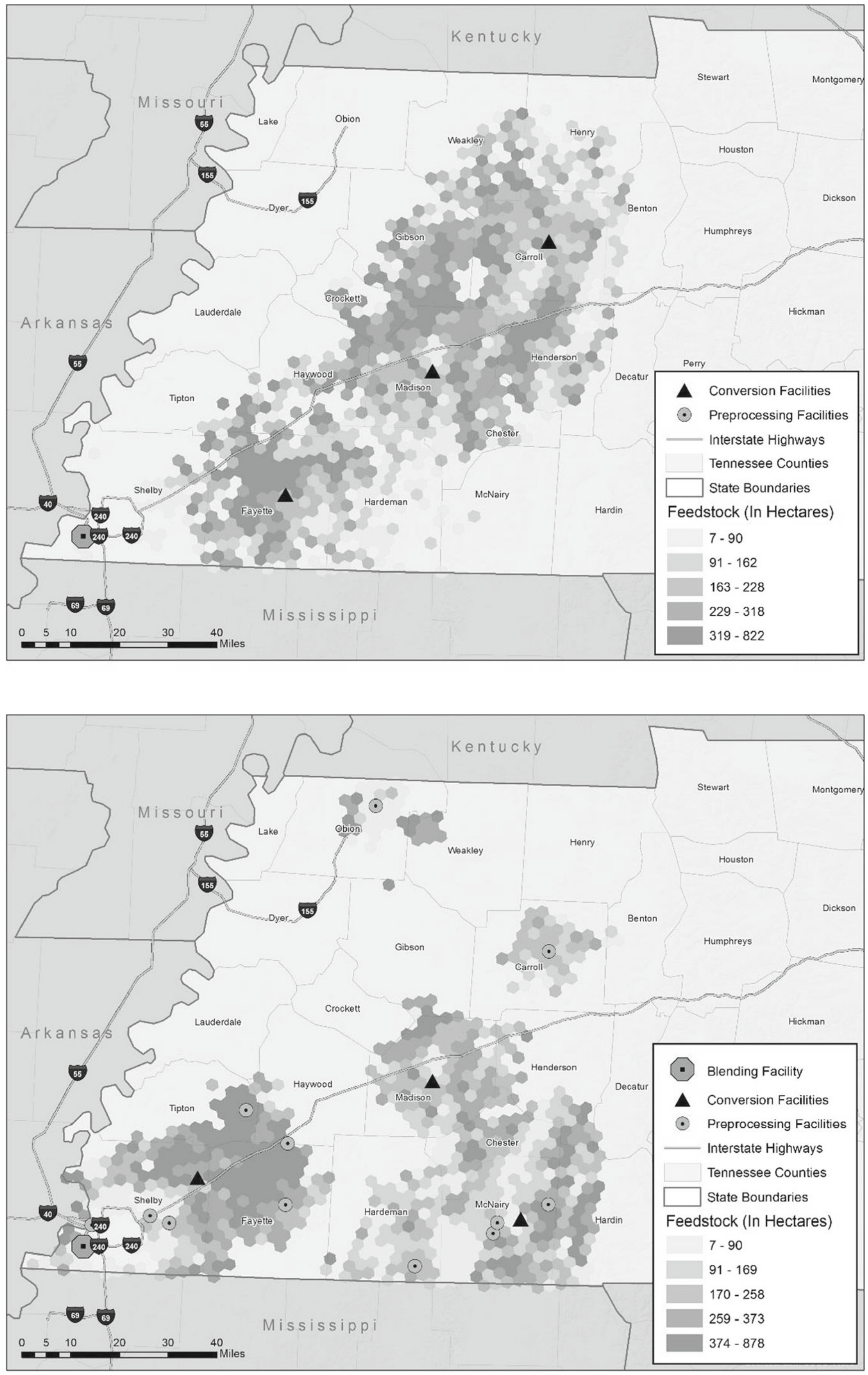
The locations of the conversion facilities and feedstock-draw areas for systems (a) and (c) are presented in Fig. 3. The choice of biorefinery locations was driven by the proximity to the switchgrass supply and blending site in Memphis metropolitan area from available industrial parks in the region. The location of conversion facilities in system (a) and (b) were identical due to their similar operation procedure.[2] The three conversion facilities were located close to switchgrass supply areas because the truckloads of hauling feedstock to each facility are greater than the truckloads of ethanol delivery from the facility to blending site. The feedstock-draw areas in

[2] Map of system (b) is not included because of the same location of conversion facilities and very similar feedstock-draw area as system (a), but is available from the authors upon request.

Fig 3 Switchgrass supply area for biofuel supply chains (**a**) and (**c**). BSC (**a**): large round balers; BSC (**c**): choppers and stretch-wrap balers

BSC (a)

BSC (c)



systems (a) and (b) are also alike but the total area for system (b) is slightly larger because of higher dry-matter loss of the larger square bales during storage. In system (c), the feedstock-draw area became more geographically scattered because preprocessing facilities can collect the loose-chopped feedstock in a more remote area. The model located preprocessing facilities within reach of available feedstock areas and to transport densified wrapped bales to conversion facilities since the densified bales have a transportation advantage. In addition to the travel distance to feedstock supply area and blending site, the location of conversion facilities was also influenced by the location of preprocessing facilities to minimize total transportation cost in the system.

Table 2 presents the annual GHG emissions generated by the three BSCs. System (b) had the least total GHG emissions at 604,000 Mg, while the large round bale system (a) produced the most GHG emissions almost 676,000 Mg. Converting croplands to switchgrass increased carbon sequestration in soils. Hay and pastureland had

Table 2 Total annual GHG emissions (CO_2e) in evaluated biofuel supply chains (BSC)

	Unit	Biofuel supply chain		
		(a)	(b)	(c)
Annual land use change GHG	CO_2e Mg	(44,377)	(45,503)	(44,572)
Annual switchgrass maintenance GHG	CO_2e Mg	11,951	11,986	12,464
Annual switchgrass harvest and storage GHG	CO_2e Mg	249,634	182,601	79,143
Annual switchgrass preprocessing and storage GHG	CO_2e Mg	–	–	126,944
Annual switchgrass transportation GHG	CO_2e Mg	22,927	19,083	45,658
Annual switchgrass grinding GHG	CO_2e Mg	99,590	99,590	58,757
Annual biofuel conversion GHG	CO_2e Mg	325,590	325,590	325,590
Annual biofuel transportation GHG	CO_2e Mg	10,299	10,319	8892
Total annual GHG emissions	CO_2e Mg	675,612	603,665	612,877

BSC (a): large round balers; BSC (b): large square balers; BSC (c): choppers and stretch-wrap balers

Eqv-CO_2 is a global warming potential term; it is the direct release of carbon dioxide (CO_2) which includes emissions of methane (CH_4) and nitrous oxide (N_2O) that have been converted into a CO_2 equivalent value using conversion factors representing the relative warming potential of the gaseous compound to the warming potential of atmospheric CO_2

higher estimated rates of carbon sequestration than switchgrass, so carbon was released from soils when the land was converted to switchgrass [43]. Around 44,000 Mg of CO_2e were stored in soils within systems (a) and (c), while more than 45,000 Mg of soil carbon was captured in system (b). System (a) emitted the most GHG emission during harvest and storage operations because the large round baler had lower throughput. System (c) had the lowest GHG emissions during harvest because of the single-pass operation; however, additional GHG emissions (nearly 127,000 Mg of CO_2e) were emitted during preprocessing and storage. The locations of conversion facilities and feedstock-draw areas affected transportation emissions considerably. Feedstock and biofuel transportation emissions in system (c) were the highest (more than 45,000 Mg of CO_2e), given the longer travel distances and more truckloads hauled due to the lower density of chopped materials.

Table 3 shows vehicle km traveled (VKT) for switchgrass and biofuel transportation. The scattered feedstock-draw area in system (c) resulted in almost 49 million km for feedstock delivery and 8 million km for biofuel transportation in west Tennessee per year. In contrast, the more compact feedstock-draw area in system (b) created the least annual travel distance with 13 million km for switchgrass shipment and more than 9 million km for biofuel delivery to the blending site. In addition to GHG emissions, biomass, and biofuel shipments created air pollutants (NO_x, $PM_{2.5,}$ and PM_{10}). Driven by higher VKT, system (c) generated the most NO_x (about 491 Mg), while system (b) produced the least NO_x (262 Mg) from transportation. A similar pattern was observed for particulate matter from feedstock and biofuel transportation. The total $PM_{2.5}$ and PM_{10} produced from transportation in system (c) was about 19 and 21 Mg, respectively.

Figure 4 presents the biofuel price sensitivity analysis results for the NPV of profit in three BSCs. Lowering biofuel price from the base case ($1.14 L^{-1}) by 15 % ($0.97 L^{-1}) and 30 % ($0.80 L^{-1}) reduced the annual revenue of biofuel sales in all BSCs, resulting a reduction in the NPV of profit. Particularly, the two baling BSC, systems (a) and (b),

Table 3 Air pollutants from transportation in evaluated biofuel supply chains (BSC)

	Unit	Biofuel supply chain		
		(a)	(b)	(c)
Transportation VKT–switchgrass	1000 km	16,089	13,391	48,870
Transportation VKT–biofuel	1000 km	9758	9779	8039
NO_x emissions from transportation in BSC	Mg	295.8	262.4	490.7
PM_{10} emissions from transportation in BSC	Mg	16.1	14.1	20.7
$PM_{2.5}$ emissions from transportation in BSC	Mg	14.5	12.7	18.6

BSC (a): large round balers; BSC (b): large square balers; BSC (c): choppers and stretch-wrap balers. *VKT* vehicle km traveled

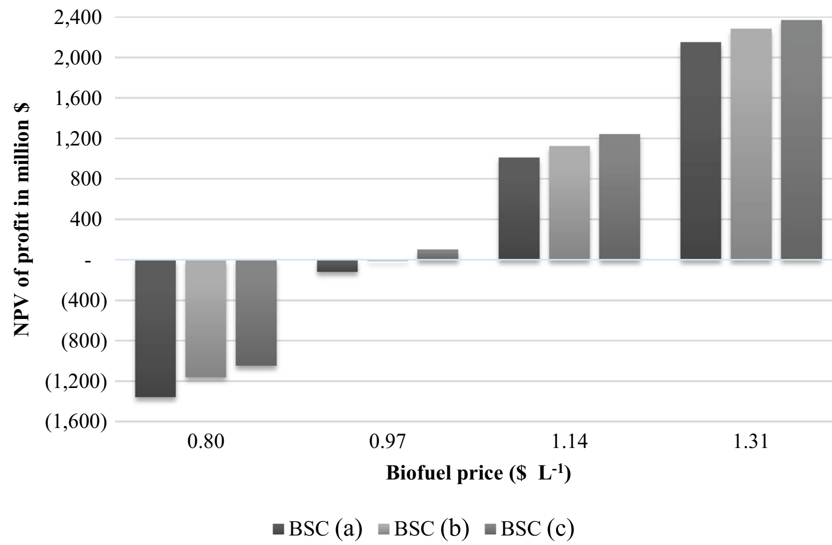


Fig 4 Sensitivity analysis of cellulosic ethanol price on NPV of profit in biofuel supply chains (**a**–**c**). BSC (**a**): large round balers; BSC (**b**): large square balers; BSC (**c**): choppers and stretch-wrap balers. The base case of biofuel price is \$1.14 L^{-1}

encountered a negative NPV when biofuel price decreased to \$0.97 L^{-1} or lower. A small NPV of profit (\$102 million) was maintained in system (c) when biofuel price declined by 15 %, but NPV turned to negative if biofuel price dropped further. It suggests that the breakeven price of biofuel for these three systems was around \$0.97 L^{-1}. When biofuel price increased to the high end of the price over the past 5 years, the NPV of profit reached above \$2100 million for all three systems.

Figure 5 presents sensitivity analysis with respect to capital scaling factor of facility investment. When the economies of scales of capital facility improves, the capital cost is reduced for both conversion and preprocessing facilities, hence the higher NPV of profit. In the analysis, the large capacity of conversion facilities (380 L) was selected regardless of the change of scaling factor in facility capital, suggesting that the savings in capital cost from economies of scale dominated the increases in feedstock transportation cost for the larger biorefineries.

Conclusions

Driven by increasing interest in developing a commercial-scale cellulosic biofuel industry in the USA, the efficiency of the BSC from the field to the distribution center has gained recent attention. In addition, the potential environmental impact of the BSC has become a crucial factor in determining the sustainability of this industry. This study optimized the NPV of profit for three switchgrass-based BSCs with different feedstock harvesting and storage configurations in west Tennessee. A mixed-integer mathematical programming model with high-resolution spatial data was used to determine the optimal location and capacity of conversion facilities and preprocessing facilities, and related feedstock-draw areas by maximizing the NPV of profit over 20 years. The optimized outputs were used to estimate annual GHG emissions produced by the BSC, including land use change, diesel consumption for agricultural activities, electricity use in

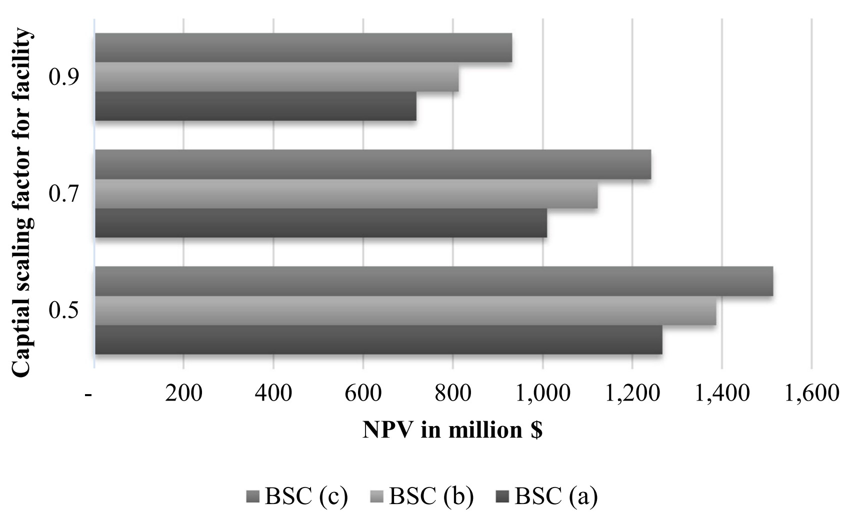


Fig 5 Sensitivity analysis of scaling factor on NPV of profit in biofuel supply chains (**a**–**c**). BSC (**a**): large round balers; BSC (**b**): large square balers; BSC (**c**): choppers and stretch-wrap balers. The base case of capital scaling factor is 0.7

preprocessing and conversion operations, and fuel use in feedstock and biofuel transportation. The other annual air pollutants (NO_x, $PM_{2.5}$, and PM_{10}) from feedstock and biofuel transportation were also estimated.

Results indicate that the harvest and storage configurations in the BSC affected the NPV of profit. The BSC system that harvested feedstock with forage choppers and utilized stretch-wrap balers to increase feedstock density had a higher NPV than the BSC systems that used traditional agricultural balers for harvest and storage. Savings in feedstock harvesting cost and feedstock size reduction cost at conversion facilities outweighed increases in preprocessing cost and feedstock transportation cost in the chopping/densification system. The large round baler system was the most costly and had the lowest NPV. Zhang et al. [10] also found the loose-chopped BSC system with preprocessing had the lowest cost. However, they found that the large square baler BSC system had the highest cost instead of the large round baler system. The average feedstock cost at the gate of conversion facilities prior to densification to powder for conversion ranged between \$82 and \$88 Mg^{-1}, falling in the range of the estimates in previous studies. Including grinding cost pushed the feedstock cost to \$101 to \$110 Mg^{-1} with the stretch-wrap baler system as the most economic BSC among the three.

When evaluating the GHG emissions produced from the field to the biofuel blending site, the large square baler system had the lowest GHG emissions, followed by the chopping/densification system, and the large round baler system, which produced the most GHG emissions. Similar findings in Kaliyan et al. [12] also suggest that the feedstock cost and life cycle GHG emissions of the large round baler system were higher than large square baler system in the US Midwest. Biofuel conversion accounted for the largest component of the GHG emissions (48–54 %) produced by the three BSC systems. In system (c), the preprocessing operation accounted for more than 20 % of total GHG emissions. The transportation component (feedstock and biofuel transportation) accounted for between 5 and 9 % of total GHG emissions. The GHG emissions resulting from indirect land use change (ILUC) was not considered in this study since the system boundary of the three BSC systems was set from field to the blending site in west Tennessee. Thus, the total life cycle GHG emissions of the BSCs will be higher if ILUC was taken into account. However, the comparison of GHG emissions from these three systems is not likely affected by ILUC since we believe that ILUC will be close to the same for evaluated systems.

Sensitivity analysis shows that a lower biofuel price reduced the NPV of all BSCs, and the breakeven biofuel price for these three systems to maintain a positive NPV of profit was around \$0.97 L^{-1}. Moreover, selection of the facility size was also influential to the cost and NPV of profit for evaluated systems, and the savings in capital cost from economies of scale dominated the increases in feedstock transportation cost for the larger biorefineries in this study.

The study shows that BSC configurations have important implications for the economic and environmental performance of the system. The harvest and storage configurations affect the location of conversion and preprocessing facilities, and associated feedstock-draw areas, hence impacting the cost and emissions of both feedstock and biofuels transportation. This study provides insights into the economic and environmental outcomes of a BSC. The findings offer useful information for planning large-scale commercial biofuel operations in Tennessee and the southeast.

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Compliance with Ethical Standards

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Conflict of Interest The authors declare that they have no competing interests.

References

1. U.S. Congress (2007) Energy independence and security act of 2007. Available at: http://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf . Accessed 5 March 2013
2. U.S. Department of Energy (2007) Roadmap for bioenergy and biobased products in the United States. Report of the biomass research and development technical advisory committee. U.S. Department of Energy, Biomass Research and Development Initiative, Washington
3. An H, Wilhelm WE, Searcy SW (2011) Biofuel and petroleum-based fuel supply chain research: a literature review. Biomass Bioenergy 35:3763–3774
4. De Meyer A, Cattrysse D, Rasinmaki J, van Orshoven J (2014) Methods to optimise the design and management of biomass-for-bioenergy supply chains: a review. Renew Sust Energ Rev 31:657–670
5. Yu TE, Wang Z, English BC, Larson JA (2014) Designing a dedicated energy crop supply system in Tennessee: a multiobjective optimization analysis. J Agric Appl Econ 46(3):357–373
6. Sharma B, Ingalls R, Jones C, Khanchi A (2013) Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future. Renew Sust Energ Rev 24:608–627
7. Kumar A, Sokhansanj S (2007) Switchgrass (*Panicum vigratum*, L) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. Bioresour Technol 98:1033–1044
8. Sokhansanj S, Mani S, Turhollow A, Kumar A, Bransby D, Lynd L, Laser M (2009) Large-scale production, harvest and logistics of switchgrass (*Panicum Virgatum* L) – current technology and envisioning a mature technology. Biofuels Bioprod Biorefin 3: 124–141

9. Larson JA, Yu T, English BC, Mooney DF, Wang C (2010) Cost evaluation of alternative switchgrass producing, harvesting, storing, and transporting systems and their logistics in the southeastern US. Agric Financ Rev 70:184–200
10. Zhang J, Osmani A, Awudu I, Gonela V (2013) An integrated optimization model for switchgrass-based bioethanol supply chain. Appl Energy 102:1205–1217
11. Kaliyan N, Morey RV, Tiffany DG (2015) Economic and environmental analysis for corn stover and switchgrass supply logistics. Bioenerg Res 8:1433–1448
12. Daystar J, Gonzalez CR, Venditti RA, Treasure T, Abt R, Kelley S (2014) Economics, environmental impacts, and supply chain analysis of cellulosic biomass for biofuels in the southern US: pine, eucalyptus, unmanaged hardwoods, forest residues, switchgrass, and sweet sorghum. Bioresources 9:393–444
13. Jäppinen E, Korpinen OJ, Ranta T (2013) The effects of local biomass availability and possibilities for truck and train transportation on the greenhouse gas emissions of a small-diameter energy wood supply chain. Bioenerg Res 6:166–177
14. Archer DW, Johnson M (2012) Evaluating local crop residue biomass supply: economic and environmental impacts. Bioenerg Res 5:699–712
15. Jäppinen, E, Korpinen OJ, Ranta T (2011) Effects of local biomass availability and road network properties on the greenhouse gas emissions of biomass supply chain. ISRN Renewable Energy. Article ID 189734: 6 pages
16. Wright L, Turhollow A (2010) Switchgrass selection as a “model” bioenergy crop: a history of the process. Biomass Bioenergy 34: 851–868
17. Humbird, D, Davis R, Tao L, Kinchin C, Hsu D, Aden A, Schoen P, Lukas J, Olthof B, Worley M, Sexton D, Dudgeon D (2011) Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol. National Renewable Energy Laboratory and Harris Group. Technical Report No. NREL/TP-5100-47764 May
18. McLaughlin SB, Kszos LA (2005) Development of switchgrass (Panicum virgatum) as a bioenergy feedstock in the United States. Biomass Bioenergy 28:515–535
19. Mooney DF, Larson JA, English BC, Tyler DD (2012) Effect of dry matter loss on profitability of outdoor storage of switchgrass. Biomass Bioenergy 44:33–41
20. Yu TE, He L, English BC, Larson JA (2014) GIS-based optimization for advanced biofuels supply chains: a case study in Tennessee. Lecture Notes Manag Sci 6:217–227
21. Song F, Zhao J, Swinton SM (2011) Switching to perennial energy crops under uncertainty and costly reversibility. Am J Agric Econ 93(3):768–783
22. Jager HI, Baskaran LM, Brandt CC, Davis EB, Gunderson CA, Wullschleger SD (2010) Empirical geographic modeling of switchgrass yields in the United States. GCB Bioenergy 2:248–257
23. U.S. Department of Agriculture, National Agricultural Statistics Service (2011) CropScape−Cropland Data Layer Database. Available at: http://nassgeodata.gmu.edu/CropScape. Accessed 18 February 2013
24. U.S. Department of Agriculture. Nature Resources Conservation Service (2012) Soil survey geographic (SSURGO) database. Available at: http://soils.usda.gov/survey/geography/ssurgo/. Accessed 25 April 2012
25. U.S. Department of Agriculture, National Agricultural Statistics Service (2010) Crop values: 2010 summary. Available at: http://usda.mannlib.cornell.edu/usda/current/CropValuSu/CropValuSu-02-16-2011.pdf. Accessed 29 November 29 2013
26. USDA NASS (2012) Tennessee farm facts. Vol. 12;14. Available at: http://www.nass.usda.gov/Statistics_by_State/Tennessee/Publications/Farm_Facts/ff091812.pdf
27. University of Tennessee Extension (2009) Guideline switchgrass establishment and annual production budgets over three year planning horizon, E12-4115-00-001-08, Knoxville, TN. Available at: http://economics.ag.utk.edu/budgets/2009/Switchgrass2009.pdf. Accessed 9 July 2013
28. U.S. Census Bureau, Geography Division, Geographic Products Branch. (2012) Topologically integrated geographic encoding and referencing (TIGER/Line®) Shapefiles. Available at: http://www.census.gov/geo/www/tiger. Accessed 5 November 2012
29. Höltinger S, Schmidt J, Schönhart M, Schmid E (2014) A spatially explicit techno-economic assessment of green biorefinery concepts. Biofuels Bioprod Biorefin 8:325–341. doi:10.1002/bbb.1461
30. Wang MC, Saricks C, Santini D (1999) Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions. U.S. Department of Energy, Argonne National Laboratory, Center for Transportation Research, Argonne
31. U.S. Energy Information Administration (2014) Tennessee state energy profile. Available at: http://www.eia.gov/state/print.cfm?sid=TN. Accessed 10 July 2014
32. Donahue DJ, Meyer S, Thompson W (2010) RIN risks: using supply and demand behavior to assess risk in the markets for renewable identification numbers used for renewable fuel standard compliance. Proceedings of the NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management. St. Louis, MO
33. Parton WJ, Hartman M, Ojima D, Schimel D (1998) DAYCENT and its land surface submodel: description and testing. Glob Planet Chang 19:35–48
34. Argonne National Laboratory (2013) The greenhouse gases, regulated emissions, and energy use in transportation model (GREET). Available at: http://greet.es.anl.gov. Accessed 5 March 2013
35. U.S. Energy Information Administration (2014) State electricity profiles. Available at: http://www.eia.gov/electricity/state/tennessee/. Accessed 6 May 2014
36. Intergovernmental Panel on Climate Change (2011) IPCC special report on renewable energy sources and climate change mitigation. Prepared by Working Group III of the IPCC. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, von Stechow C (eds). Cambridge University Press, New York, NY, USA
37. Hsu D, Inman D, Heath GA, Wolfrum EJ, Mann MK, Aden A (2010) Life cycle environmental impacts of selected US ethanol production and use pathways in 2022. Environ Sci Technol 44: 5289–5297
38. U.S. Environmental Protection Agency (EPA) Development of emission rates for heavy-duty vehicles in the motor vehicle emissions simulator MOVES2010—final report. Assessment and Standards Division Office of Transportation and Air Quality: EPA-420-B-12-049. August 2012. Available at: http://www.epa.gov/otaq/models/moves/index.htm
39. Jack MW (2009) Scaling laws and technology development strategies for biorefineries and bioenergy plants. Bioresour Technol 100: 6324–6330
40. Kocoloski M, Griffin WM, Matthews HS (2011) Impacts of facility size and location decisions on ethanol production cost. Energy Policy 39:47–56
41. Haque M, Epplin FM, Biermacher JT, Holcomb RB, Kenke PL (2014) Marginal cost of delivering switchgrass feedstock and producing cellulosic ethanol at multiple biorefineries. Biomass Bioenergy 66:308–319
42. Khanna M, Dhungana B, Brown JC (2008) Costs of producing miscanthus and switchgrass for bioenergy in Illinois. Biomass Bioenergy 32:482–493
43. Kwon HY, Mueller S, Dunn JB, Wander MM (2013) Modeling state-level soil carbon emission factors under various scenarios for direct land use change associated with United States biofuel feedstock production. Biomass Bioenergy 55:299–310