GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2015), doi: 10.1111/gcbb.12241

Biomass feedstock preprocessing and long-distance transportation logistics

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Abstract

Biomass-based biofuels have gained attention because they are renewable energy sources that could facilitate energy independence and improve rural economic development. As biomass supply and biofuel demand areas are generally not geographically contiguous, the design of an efficient and effective biomass supply chain from biomass provision to biofuel distribution is critical to facilitate large-scale biofuel development. This study compared the costs of supplying biomass using three alternative biomass preprocessing and densification technologies (pelletizing, briquetting, and grinding) and two alternative transportation modes (trucking and rail) for the design of a four-stage biomass–biofuel supply chain in which biomass produced in Illinois is used to meet biofuel demands in either California or Illinois. The BioScope optimization model was applied to evaluate a four-stage biomass–biofuel supply chain that includes biomass supply, centralized storage and preprocessing (CSP), biorefinery, and ethanol distribution. We examined the cost of 15 scenarios that included a combination of three biomass preprocessing technologies and five supply chain configurations. The findings suggested that the transportation costs for biomass would generally follow the pattern of coal transportation. Converting biomass to ethanol locally and shipping ethanol over long distances is most economical, similar to the existing grain-based biofuel system. For the Illinois–California supply chain, moving ethanol is \$0.24 gal^{-1} less costly than moving biomass even in densified form over long distances. The use of biomass pellets leads to lower overall costs of biofuel production for long-distance transportation but to higher costs if used for short-distance movement due to its high capital and processing costs. Supported by the supply chain optimization modeling, the cellulosic-ethanol production and distribution costs of using Illinois feedstock to meet California demand are \$0.08 gal^{-1} higher than that for meeting local Illinois demand.

Keywords: biomass, cost, modeling and analysis, optimization, preprocessing, supply chain, transportation

Received 7 October 2014; accepted 21 November 2014

Introduction

Biofuel from cellulosic biomass such as agricultural residues, dedicated energy crops, and woody material has gained attention due to its potential to contribute to energy independence, climate change mitigation, and rural economic development (Hill *et al*., 2006). Cellulosic biomass resources are, however, geographically widely distributed and have an inherently low energy and mass density. Transporting biomass efficiently and effectively is critical for large-scale cellulosic biofuel production.

Given the nature of agricultural supply and demand, the design of a biomass–biofuel supply chain can initially be modeled after existing grain-food systems. In a typical grain-food system in the United States, grain is hauled by trucks from fields to grain elevators and centralized facilities for better access to transportation networks. The processed agricultural products are then transported to centralized food production facilities and distribution centers by trucks and rail cars. Similar to the grain-food supply chain systems, a typical biomass–biofuel supply chain having many suppliers and few processing facilities can be designed to gain economies of scale.

Biomass feedstock has an inherently low mass and energy density, which results in economic constraints for large-scale biofuel production. Biomass feedstock is normally collected in the form of bales from distributed farm fields and can be preprocessed through size

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reduction and densification. Biomass preprocessing has been identified as a component that can improve system-level efficiency of large-scale biomass–biofuel production (Hess *et al*., 2007; Eranki *et al*., 2011; Lin *et al*., 2013). A four-stage biomass–biofuel supply chain is proposed in this work to include biomass production, centralized storage and preprocessing (CSP), biorefinery, and ethanol distribution (Fig. 1). Similar to elevators in the grain supply chain system, CSP is designed to store biomass and provide a consistent raw material format through preprocessing. Grinding, briquetting, and pelletizing are the three major preprocessing technologies to improve biomass density relative to bales.

Geographically, major biomass supply and biofuel demand areas are noncontiguous in the United States. While rainfed agricultural land is located primarily in the Midwest and the South, major transportation fuel demands are located on the east and west coasts. Locally grown biomass feedstock is not sufficient to support large-scale ethanol demand on both coasts, and thus long-distance transportation of biomass or ethanol would be required. For example, California has proposed low carbon fuel standard to lower the carbon intensity of transportation fuel using biofuels and other renewable sources (California's Low Carbon Standard Program, 2013). It is impossible for California to meet this goal by in-state sourcing alone. Critical biomass supply chain system design and planning will determine whether this goal can be met either by building processing facilities near feedstock production combined with transporting biofuel from other states or by building biorefineries in California and transporting biomass from other states.

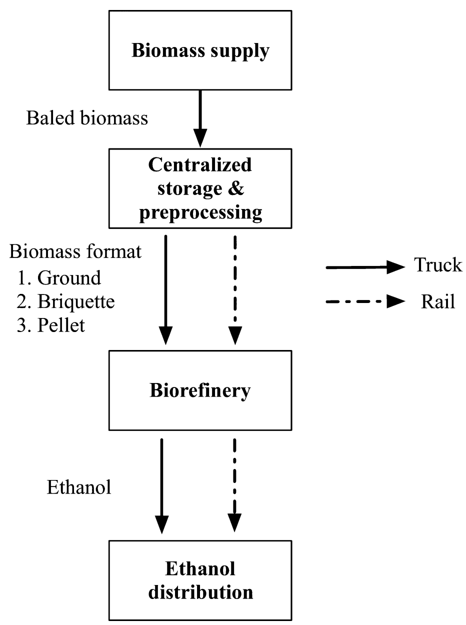

Fig. 1 Four-stage biomass–biofuel supply chain.

The optimum supply chain configuration depends on the technology of biomass preprocessing, the mode of transportation, and the locations and capacities of biomass supply and processing facilities. Biomass supply chain and logistics analysis have been reported in earlier studies, in terms of the cost analysis of various transportation modes (Searcy *et al*., 2007), preprocessing technologies and delivery types (Sultana & Kumar, 2011), and economy of scale benefits (Sokhansanj *et al*., 2009). However, an integrated decision support tool that optimizes the whole supply chain configuration considering the interactions and trade-offs among components within the system is lacking. A system-level supply chain evaluation, from feedstock sourcing to preprocessing to ethanol conversion and distribution, is needed to understand the optimal solutions for biomass–biofuel production. Trade-offs exist between preprocessing costs and transportation costs under various preprocessing conditions. For example, a greater density of biomass results in lower transportation costs due to the reduced volume of densified material, but it requires higher preprocessing costs due to the increased complexity of preprocessing.

To better understand the characteristics of a biomass–biofuel supply chain, this study has two key objectives: (1) to analyze the trade-off between costs of biomass preprocessing and transportation costs and (2) to identify the least cost approach of biofuel production among a range of supply chain configuration options for biomass producing, preprocessing, transporting and biorefinery. We specifically consider the case of biomass produced in Illinois to meet ethanol demands in both California and Illinois to demonstrate the interactions among biomass preprocessing technology, transportation mode, optimal biomass supply area, and facility location and capacity decisions. The selection of the Illinois-to-California biomass supply chain is hypothetical, but it addresses real needs imposed by recent low carbon energy mandates in the state of California. More generally, the scenarios explore the relative costs associated with using current processing technologies and existing transportation infrastructure for both short and long-distance transportation.

Materials and methods

Supply chain optimization model description

The optimization of a large-scale biomass–biofuel supply chain system was conducted using a modified BioScope model. It was developed based on the initial version of the BioScope model (Lin *et al*., 2013) that focused on a three-stage supply

 GCB Bioenergy, doi: 10.1111/gcbb.12241

chain system including biomass supply, CSP, and biorefinery. The analysis scope of the modified BioScope model developed in this study extends to ethanol distribution to consider a complete biomass–biofuel supply chain from biomass provision to ethanol end uses (Fig. 1).

The objective of the optimization model is to minimize the annual biomass–biofuel production costs (Z) that are comprised of five costs: biomass procurement costs (C_B), transportation related costs (C_T), CSP related costs (C_S), biorefinery related costs (C_E), and ethanol distribution costs (C_D) [Eqn (1)].

$$\text{Minimize } Z = C_B + C_T + C_S + C_E + C_D. \qquad (1)$$

The model has several key inputs that can be grouped from spatial, agricultural, and engineering/technology perspectives (Fig. 2). Spatial information includes candidate locations for biomass supply, CSP, biorefinery facilities, and ethanol distribution centers, as well as transportation distances among candidate locations. Agricultural information includes biomass yield, cropland usage rate for biomass crop production, and biomass provision costs. Engineering and technology inputs include unit transportation costs for various transportation modes, and unit operating and capital costs for various preprocessing technologies and biomass–biofuel conversion technologies.

The optimization model is a mixed integer linear programing model that has been developed on the GAMS platform (GAMS, 2013) and solved using the CPLEX® solver. Piecewise linearization functions have been incorporated in the model to take into account economies of scale for facilities. The detailed model descriptions including constraint equations have been reported in Lin *et al*. (2013). For a typical biomass supply chain system, large processing facilities can reduce the unit production costs as a result of economies of scale. The larger the facility capacity, the larger the biomass feedstock supply area, and accordingly the higher the transportation related costs. Overall, given the biomass supply and demand constraints, the model balances key trade-offs between facility costs and biomass feedstock provision costs. The key decision variables include the optimal number, location, and capacity of biomass supply sites, CSPs, and biorefineries as well as the optimal biomass flow patterns from farms to CSPs to biorefineries and ethanol flow patterns from biorefineries to ethanol distribution centers.

The optimization model was solved at county-level resolution, aggregating distributed biomass supplies within a county to one point. Given good access to the transportation network, county seats were used as a representative for biomass supply locations. The candidate locations of CSP and biorefinery facilities were selected based on road and rail network infrastructures. Based on the county-level *Miscanthus* yield data (Jain *et al*., 2010) and cropland area (USDA, 2009), county-level biomass availability was estimated. County-level biomass procurement costs comprised biomass establishment costs (Jain *et al*., 2010), land opportunity costs (Jain *et al*., 2010), and biomass production costs. Biomass production costs included the costs of biomass harvesting, baling, infield transportation, and within county transportation. County-level biomass production costs were optimized using the BioFeed model considering the impact of farm size and biomass yield (Lin *et al*., 2013).

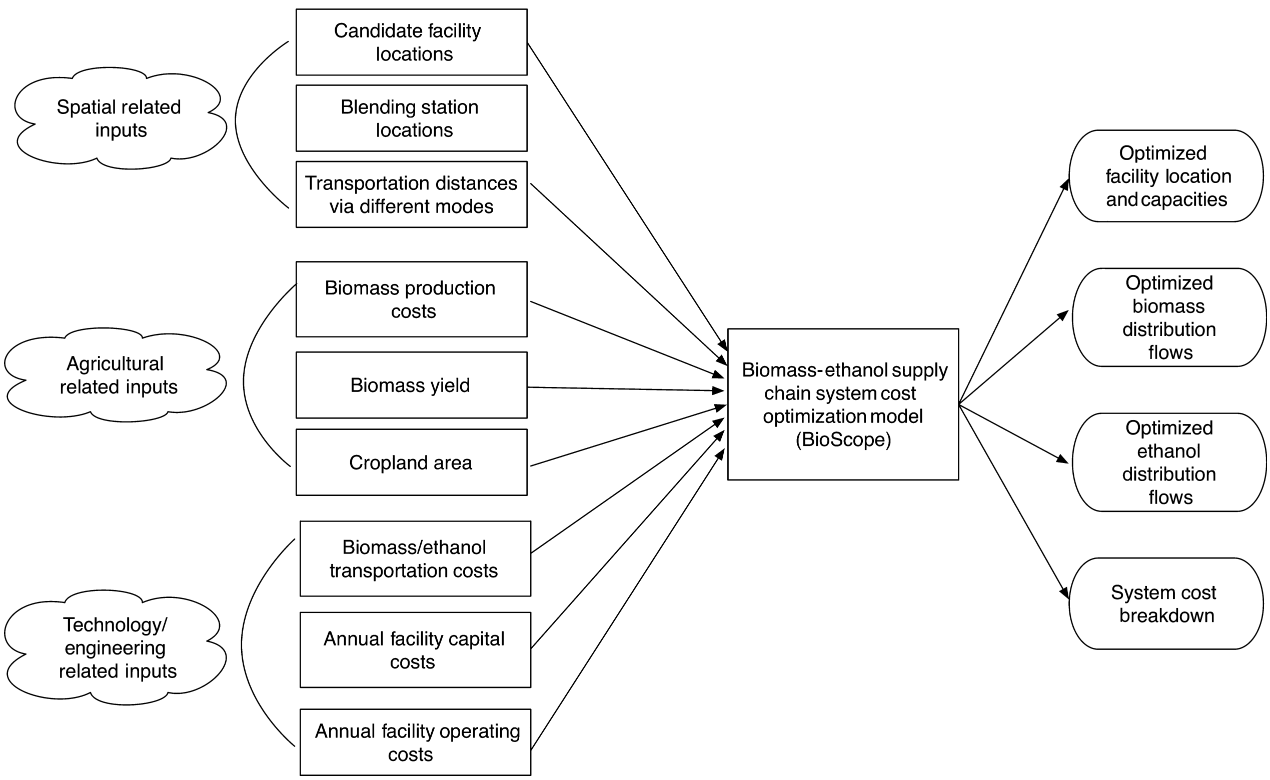

Fig. 2 Input and output diagram of the BioScope model.

Cropland use change for dedicated energy crop production is a critical decision for farmers. In this study, we considered *Miscanthus*, a dedicated perennial energy crop that requires a long-term commitment of land usage by farmers. It was assumed that the cropland usage rate for *Miscanthus* varies with distance between farms and the nearest CSP facilities. In the current study, the cropland conversion rate of a county can be increased up to 7% if it is located within a 100 km radius from a CSP facility, up to 5% within a 200 km radius, and up to 3% beyond 200 km.

The changes of cropland usage rate, transportation cost, and biomass demand have been evaluated to significantly affect the biomass provision costs and supply chain configurations within the state of Illinois (Lin *et al.*, 2013). This study is focused on the impact of preprocessing technology and transportation mode on biomass–biofuel supply chain systems.

Biomass densification technologies

Grinding, briquetting (cubing), and pelletizing are three physical densification processes with differences in the levels of output biomass density. All physical densification processes have three major steps including drying, size reduction, and densification. Hammer mills (Mani *et al.*, 2006) and tub grinders (Arthur *et al.*, 1982) have been used for size reduction or grinding of various forage crops, grains, and biomass materials. The reduced particle size increases the total surface area and pore size of the material and reduces cellulose crystallinity. The finely ground biomass would be further compressed to improve density. Highly densified biomass requires finer particle size and higher compression pressure, which increases the complexity of the process (Miao *et al.*, 2013). Biomass pelletizing usually requires a second size reduction process before compression (Campbell, 2007).

Bulk density is always used for transportation cost evaluation to consider porosity associated with different formats. Baled biomass is a typical format on farm with its bulk density at approximately 150 kg m^{-3} (Sokhansanj & Turhollow, 2004). Through the densification process, the bulk density of biomass can be increased to approximately 650 kg m^{-3} for biomass pellets (Sokhansanj & Turhollow, 2004). Their density is still lower than major commodities such as corn and coal (Fig. 3).

Densified biomass also improves handling efficiency. As the shape of the densified biomass is gravity flowable, similar to that of grains, it can be handled via conveying belts. By contrast, baled biomass requires forklifts for handling, which is labor intensive and less efficient.

Annualized capital and operating costs comprise biomass preprocessing costs and are a function of capacity levels. A biomass grinding system is mainly composed of biomass loaders, grinders, and conveyor systems for ground biomass discharge. Biomass loading and grinding operating costs were estimated at \$6.37 Mg^{-1} for a capacity of 100 Mg h^{-1} (Hess *et al.*, 2007). In addition to equipment needed for biomass grinding, a briquetting system requires briquetting machines, dryers, and coolers. The annualized capital and operating costs for biomass briquetting have been estimated at \$23.45 Mg^{-1} for an effective capacity of 9.4 Mg h^{-1} (Sokhansanj & Turhollow, 2004). A biomass pelletizing system includes primary grinders, hammer mills, pelletizing instrumentation, dryers, coolers, and conveyor systems. The capital costs were estimated at \$9.1 million at a capacity of 14 Mg h^{-1} (Campbell, 2007). Detailed descriptions of process, equipment requirement, and associated economic analyses have been reported for biomass grinding (Grant *et al.*, 2006; Hess *et al.*, 2007), biomass briquetting (Sokhansanj & Turhollow, 2004), and biomass pelletizing (Campbell, 2007).

Economies of scale are critical for the success of processing facilities, where power laws have been applied to predict capital investment costs (Peters & Timmerhaus, 1991). Scaling factors are typically selected between 0.6 and 0.7 for biomaterial and chemical processing facilities (Park, 1984). In this work, a

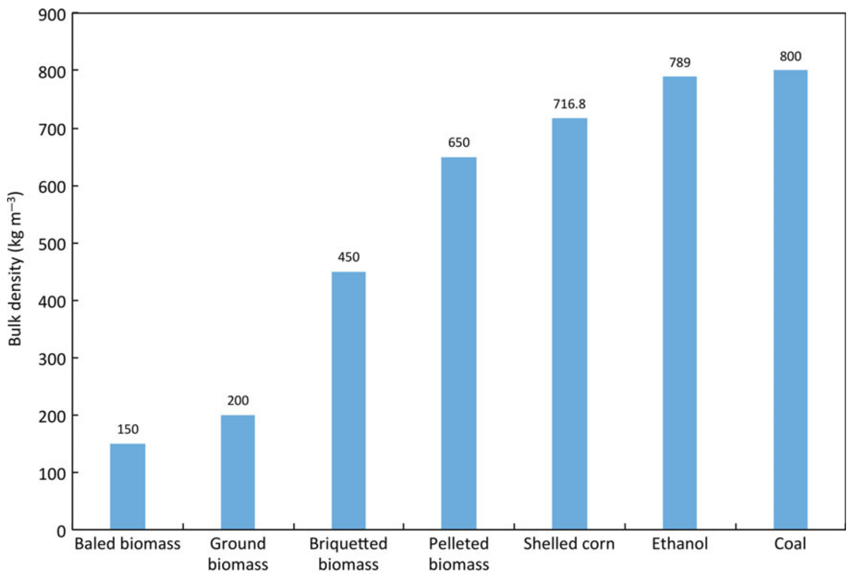

Fig. 3 Bulk densities of various materials. Densities of all materials except ethanol are on a dry matter basis.

scaling factor of 0.7 was applied to estimate the economies of scale for both CSP and biorefinery facilities at various capacities. Piecewise linear approximation was applied to linearize the cost curve into three capacity levels (Lin *et al.*, 2013), namely small (50 000–600 000 Mg yr^{-1}), medium (600 000–1 300 000 Mg yr^{-1}), and large (beyond 1 300 000 Mg yr^{-1}, Table 1). It is expected that with a larger processing scale, fixed capital costs increase while unit variable capital costs decrease. Operating costs for each process were assumed identical at various capacity levels.

Transportation modes

Truck and rail transport are two primary modes for domestic grain and ethanol transportation. Transportation costs comprise fixed costs that are not distance related, including loading and unloading costs, and distance related variable costs. Trucking is preferred for short-distance transportation because of its low fixed costs and flexibility, while rail is preferred for long-distance transportation for bulk products as a result of relatively low distance related variable costs (Mahmudi & Flynn, 2006; Searcy *et al.*, 2007). Trucking accounted for 60% of grain transportation in the domestic markets (USDA, 2013a), suggesting most grain would not be transported over long distance and would be processed close to farm production sites. Rail accounted for 60% of ethanol transportation in 2005, indicating a nationwide distribution (USDA, 2007). Given the similarity in spatial features on supply and demand, a biomass–biofuel supply chain is likely to develop similar to a grain production and distribution system. This study focuses on trucking and rail for both biomass and ethanol transportation.

Truck

Weight and volume limitations are the key constraints for truck transportation. The loading limit on major highways in the United States is typically 36.3 Mg for gross vehicle weight (Badger & Fransham, 2006). Considering the tare weight for a tractor-trailer combination at approximately 12 Mg, a net payload weight limit of 25 Mg per vehicle is a good estimate. Given a typical semitrailer sized at a length of 16 m (53 feet), a width of 2.6 m (102 inch), and a height of 2.4 m (8 feet), and its density threshold is 250 kg m^{-3}. The density threshold may vary by different types of vehicle. If the density of a material is lower than the equivalent optimum density, the amount of the material that can be transported per vehicle is limited by the volume. Otherwise, the material is limited by the weight. Grain is always limited by weight due to its high density.

Dry matter bulk density and moisture content are the two major related properties for biomass transportation. Assuming 12% moisture content, baled and ground biomass are limited by the volume due to the low density. A truck can only transport approximately 15 and 20 Mg in dry matter for baled and ground biomass, respectively. The lower payload weight would increase variable transportation costs. Based on the density and moisture content information, biomass variable transportation costs can be estimated for different densified biomass formats. Detailed trucking cost analysis can be conducted by considering annualized capital costs of trucks, traveling distances per year, and labor and fuel costs (Rogers & Brammer, 2009). Fluctuation in fuel costs acts as a key factor in trucking costs. Trucking costs for straw and wood chips were estimated at \$0.13 and \$0.11 dry matter Mg^{-1} km^{-1}, respectively (Mahmudi & Flynn, 2006).

The type of truck used to transport liquid fuel is different than that used to transport bulk products. A typical large tank truck has a capacity of 35 600 L (9500 gallons), which is equivalent to 28.5 Mg of ethanol. Ethanol trucking costs were estimated at \$0.15 Mg^{-1} km^{-1} (Morrow *et al.*, 2006).

Rail

Rail is typically applied for long-distance commodity transportation such as ethanol and coal, which are produced in certain areas but consumed nationwide. Rail transportation is usually limited by volume, not weight. Given the density of each material, the transportation capacity of a rail car for various materials can be estimated, from 20 Mg per rail car for baled biomass to more than 100 Mg per rail car for coal (Fig. 4). Liquid and bulk products require different types of rail cars. The rate of rail transportation cost is provided by \$ per rail car, which can be affected by traveling distance, the value of products moved, and the type of rail car movement (Surface Transportation Board, 2009). The distance affects the unit variable transportation costs,

Table 1 Fixed and variable costs for biomass preprocessing and biorefining technologies. The data are derived from the previous studies on biomass grinding (Hess *et al.*, 2007), biomass briquetting (Sokhansanj & Turhollow, 2004), and biomass pelletizing (Campbell, 2007), and biorefining (Humbird *et al.*, 2011)

		Biomass grinding	Biomass briquetting	Biomass pelletizing	Biorefinery
Operating costs (\$ Mg^{-1})		10	12.5	15	48
Capacity range (Mg yr^{-1})	Capital costs				
50 000–600 000	Fixed costs (\$)	3 204 700	4 944 400	6 182 400	63 709 000
	Variable costs (\$ Mg^{-1})	21.79	33.62	42.04	480.3
600 000–1 300 000	Fixed costs (\$)	8 693 400	13 413 000	16 771 000	173 237 000
	Variable costs (\$ Mg^{-1})	15.16	23.39	29	333
Above 1 300 000	Fixed costs (\$)	12 463 000	19 228 000	24 042 000	255 051 000
	Variable costs (\$ Mg^{-1})	13.04	20.12	25.15	283.2

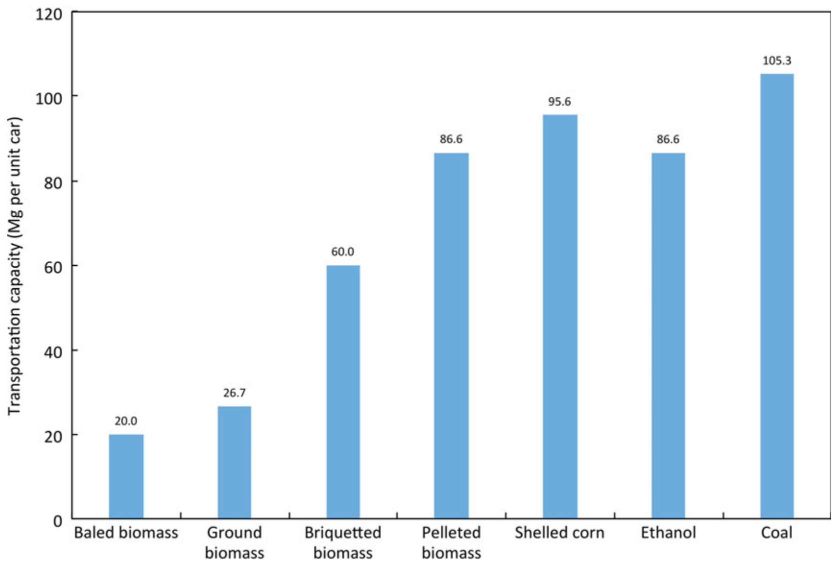

Fig. 4 Transportation capacity of a rail car for various materials. All numbers are based on dry matter weight capacity, assuming 12% moisture content for all types of biomass.

where long-distance transportation usually requires lower unit variable transportation costs, as is evident for corn, coal, and ethanol (Table 2).

Higher value products usually require higher insurance rates. Given the market price of each material as of October 24, 2013, the value of material shipped by a rail car can be estimated (Fig. 5). The insured values of a rail car movement for ethanol and corn are much higher than other products. Densified biomass has similar insured values to coal.

Considering the similar bulk size, usage, and product value, rail transportation cost for biomass was estimated based on coal transportation. It was assumed that the transportation cost for a rail car of biomass was identical to a coal shipment at the same traveling distance. Given the density differences, the transportation costs for different types of biomass are provided in Table 2. The unit transportation costs for biomass reduce with higher density and longer transportation distances.

There exist two major types of rail car movements: single rail car and unit train that usually comprises multiple rail cars.

Table 2 Rail variable transportation costs for various materials. All the numbers are in \$ Mg^{-1} km^{-1}

	Shipping distance		
	<800 km	800–1600 km	>1600 km
Baled biomass	0.171	0.073	0.045
Ground biomass	0.128	0.055	0.034
Biomass briquettes	0.057	0.024	0.015
Biomass pellets	0.039	0.017	0.010
Corn*	0.032	0.021	0.017
Ethanol†	0.051	0.031	0.024
Coal*	0.029	0.013	0.008

*Surface Transportation Board (2009).
†USDA (2007).

Most bulk materials, such as coal, steel, and grain and bulk liquids like ethanol are shipped via unit trains, especially for long-distance transportation. Unit train shipments usually require less unit transportation costs.

The costs listed Table 2 are the average costs considering both single car and unit train movements, but without considering the contract prices and fuel surcharge costs. The contract prices vary significantly from company to company and are usually determined by the transportation volume and contract duration. Recently, due to the fluctuations of oil prices, rail companies would charge fuel surcharge costs under certain conditions (USDA, 2013b). These fuel surcharge costs are not considered in this study.

Scenario description

To better understand the long-distance biomass and biofuel transportation and production costs, scenario analyses were conducted to evaluate the system performance using *Miscanthus* produced in Illinois to support an annual ethanol demand of 200 million gallons in Los Angeles, California and Chicago, Illinois. In this study, ground biomass, briquettes, and pellets are the three types of preprocessed biomass. Five supply chain configurations have been assumed to understand and evaluate combinations of transportation modes and ethanol demand destinations (Fig. 6). A total of 15 scenarios were evaluated considering five supply chain configurations and three biomass formats.

In these 15 scenarios, truck was used to haul baled biomass from farm fields to CSP facilities. After preprocessing, truck or rail transportation can be used to move preprocessed biomass to biorefineries. Truck was also used for ethanol transportation within the state, while rail was used for long-distance transportation.

We assumed five supply chain configurations (Fig. 6): (C1) *Miscanthus* is produced, preprocessed, and biorefined in

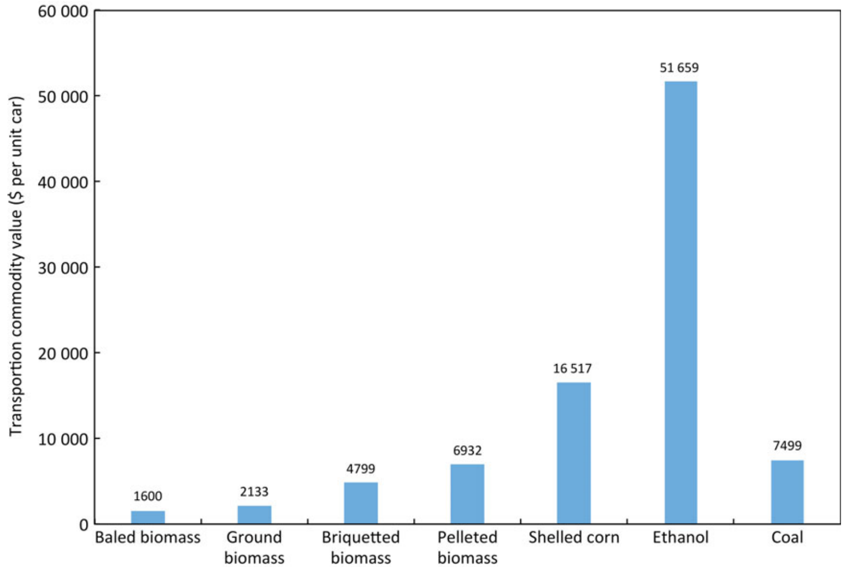

Fig. 5 Market value of various materials per rail car load. The value is based on the market prices as of October 24, 2013, when corn was \$173 Mg^{-1} (\$4.4 $bushel^{-1}$), ethanol \$596 Mg^{-1} (\$1.82 $gallon^{-1}$), and coal \$71.2 Mg^{-1}. Biomass price was assumed \$80 Mg^{-1}.

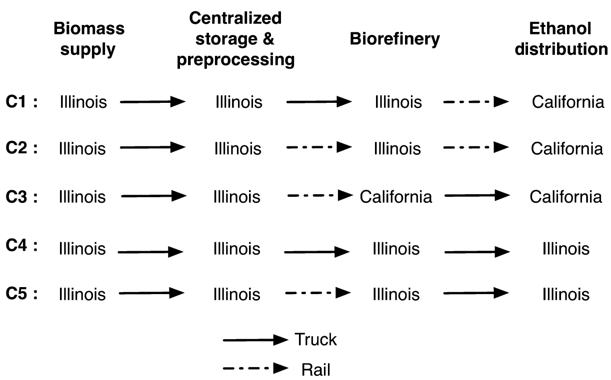

Fig. 6 Five biomass–biofuel supply chain configurations under evaluation.

Illinois. Trucking is used for preprocessed biomass transportation to biorefineries in Illinois, and rail is used for ethanol transportation to the distribution center in Los Angeles, California; (C2) *Miscanthus* is produced, preprocessed, and biorefined in Illinois. Rail is used for both preprocessed biomass transportation in Illinois and ethanol transportation to the distribution center in Los Angeles, California; (C3) *Miscanthus* is produced and preprocessed in Illinois, and this preprocessed biomass is transported via rail to Los Angeles, California for biorefining; (C4) *Miscanthus* is produced, preprocessed, and biorefined in Illinois. Trucking is used for preprocessed biomass transportation to biorefineries in Illinois and ethanol transportation to the distribution center in Chicago, Illinois; and (C5) *Miscanthus* is produced, preprocessed, and biorefined in Illinois. Rail is used for preprocessed biomass transportation, and trucking is used for ethanol transportation to the distribution center in Chicago, Illinois. Supply chain configurations in C4 and C5 are used to evaluate the differences in systems performance between long-distance transportation/production and local production.

Both trucking and rail transportation costs involve fixed and variable costs. The fixed costs for each transportation mode were assumed the same for all three biomass formats. Rail transportation requires higher fixed costs at \$6.98 Mg^{-1}, while the fixed costs for trucking were \$3.83 Mg^{-1}. The unit variable trucking transportation costs for ground biomass, briquettes, and pellets were assumed at \$0.14, \$0.13, and \$0.13 Mg^{-1} km^{-1}, respectively (Lin *et al.*, 2013). The variable rail transportation costs are related to both biomass format and transportation distance, where the input data used in this study have been provided in Table 2.

Results

For a system that requires long-distance biomass/biofuel transportation (C1, C2, and C3), building biorefineries near biomass production areas and transporting ethanol to end-use sites is a more efficient supply chain configuration with lower biomass–biofuel production costs (Table 3). The results are in agreement with the existing grain processing and ethanol production supply chain configurations, where most processing facilities are located in the Midwest where feedstocks are grown.

Furthermore, grinding and truck transportation (C1-Ground) are suggested to be the best options. The biofuel production costs can be optimized to \$2.81 gal^{-1} using truck transportation for ground biomass. (To facilitate cost comparison, all the cost results described in this section have been normalized to \$ per gallon of

Table 3 Economic comparisons of the optimized biomass–biofuel supply chain configurations. All numbers are in $ per gallon of ethanol

	C1			C2			C3			C4			C5		
	Ground	Briquette	Pellet	Ground	Briquette	Pellet	Ground	Briquette	Pellet	Ground	Briquette	Pellet	Ground	Briquette	Pellet
Total production costs	2.81	2.87	2.92	2.83	2.85	2.88	3.85	3.19	3.05	2.73	2.78	2.84	2.74	2.74	2.77
Biomass procurement	0.86	0.86	0.86	0.86	0.85	0.85	0.90	0.88	0.88	0.95	0.95	0.95	0.95	0.92	0.91
CSP related	0.20	0.26	0.32	0.19	0.26	0.31	0.20	0.26	0.31	0.19	0.25	0.29	0.18	0.25	0.31
Biomass transportation	0.22	0.22	0.22	0.25	0.21	0.20	1.45	0.74	0.56	0.20	0.19	0.21	0.22	0.24	0.22
Biorefinery related	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29
Ethanol distribution	0.24	0.24	0.24	0.24	0.23	0.23	0.01	0.01	0.01	0.10	0.10	0.10	0.10	0.04	0.04

CSP, centralized storage and preprocessing.

ethanol production costs, assuming one Mg biomass can produce 80 gallons of ethanol.)

Highly densified biomass is not economically viable for local ethanol production, because of its high capital and operating costs. Biomass pelletizing imposes an additional cost of \$0.12 gal^{-1} as compared to biomass grinding. Although highly densified biomass requires lower trucking transportation costs, relatively short transportation distances within Illinois limit the possible gains afforded by trucking, which are not sufficient to offset the increased preprocessing costs. Furthermore, for short-distance transportation, rail is not a cost-effective choice for ground biomass movement, given its relatively high fixed costs. Considering highly densified biomass scenarios, rail outperforms trucking in both short and long-distance configurations.

If biomass feedstock is needed to sustain biorefinery operations during periods with a local feedstock shortage, pellets are preferred for long-distance transportation (C3), as low-density biomass is very expensive to be moved over long distances. The biomass transportation costs are \$1.45 gal^{-1} if ground biomass is moved from Illinois to California for biorefining, which accounts for 37.7% of the biofuel production costs (Table 3). The transportation costs of moving ground biomass over long distance are even higher than biorefinery related costs. By moving biomass pellets from Illinois to California, biomass transportation costs can potentially be reduced to \$0.56 gal^{-1}, almost one-third of the costs moving ground biomass.

Comparing the scenarios that require long-distance transportation, moving ethanol over long distances is generally more cost-effective than moving biomass. The best scenario for building biorefineries in Illinois (C1-Ground) has a cost advantage of \$0.24 gal^{-1}, as compared to the best scenario of building biorefineries in California (C3-Pellet).

For a local supply–demand system (C4 and C5), the minimum biofuel production costs to support local Chicago ethanol demand can be reduced to \$2.73 gal^{-1}, with the combination of biomass grinding and trucking transportation (Table 3). The optimum costs are \$0.08 gal^{-1} lower than that for long-distance transportation (C1-Ground).

The selection of biomass preprocessing technology and transportation mode affects not only biomass–biofuel production costs, but also spatial supply chain configurations. Each scenario analysis results in its own optimal spatial supply chain configuration featured by its facility locations and biomass distribution patterns (Fig. 7). A centralized biorefinery with an annual capacity of 200 million gallons of ethanol is suggested for all 15 scenarios, aiming to achieve the economies of scale. Various biomass preprocessing technologies vary in

  doi: 10.1111/gcbb.12241

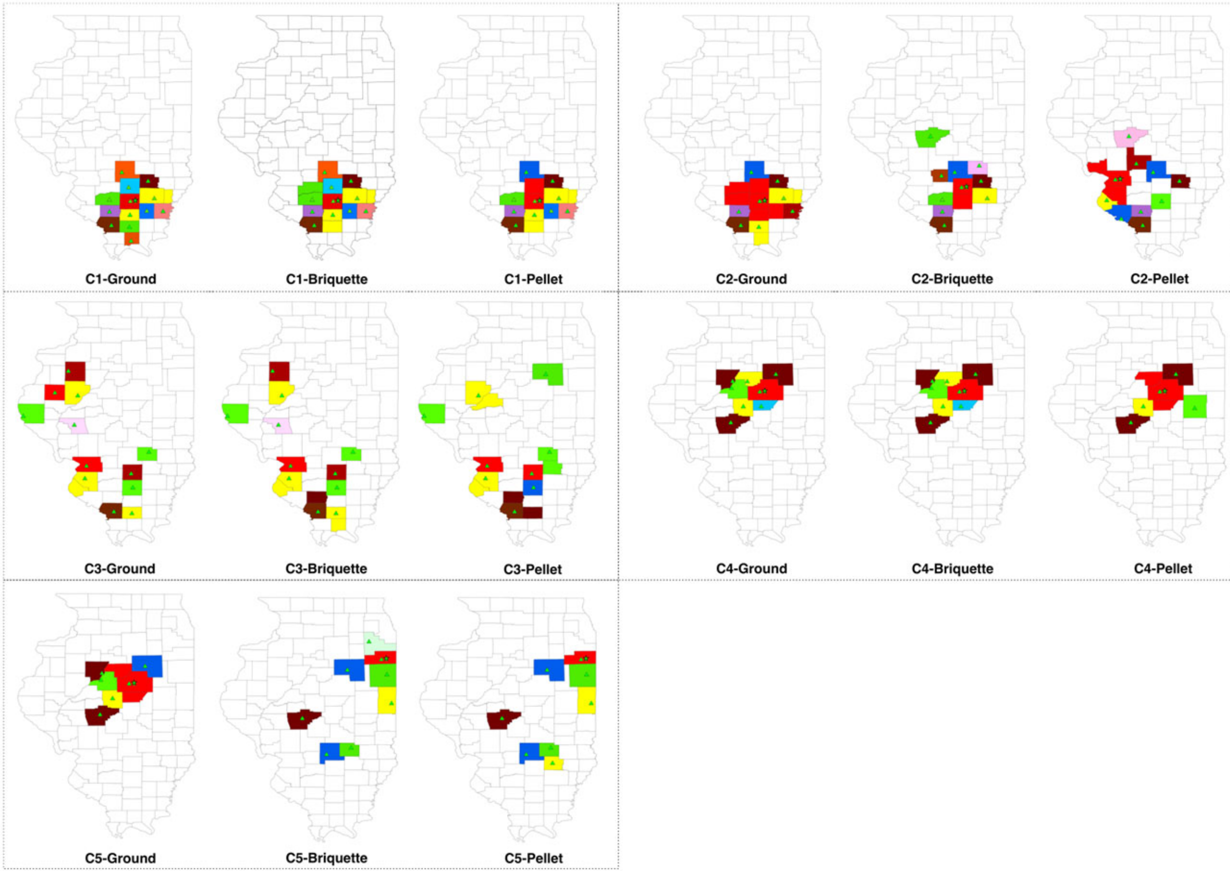

Fig. 7 The spatial visualization of 15 different optimized biomass–biofuel supply chain configurations. The triangles represent centralized storage and preprocessing centers (CSPs) and the stars represent biofuel facilities. The biofuel facilities located in California (C3) are not shown here. The colored areas represent the selected biomass supply areas. If a colored area comprises several counties, biomass produced from these counties will move to the CSP located in that colored area.

preprocessing costs, but also result in different optimal supply chain configurations. The selection of a preprocessing technology affects the optimal facility number and capacity and its associated biomass sourcing areas. The number of the CSP facilities using the pelletizing technology is smaller than that while using the other two technologies, showing that biomass pelletizing facilities have a higher design capacity on average. The increased facility capacity would require to source biomass from a larger area. The changes of selected biomass supply areas lead to the variations of biomass procurement costs.

The transportation mode has significant impact on the optimal supply chain configuration. The scenarios including trucking transportation (C1 and C4) require a centralized configuration of biomass supply counties to reduce transportation costs. By contrast, benefiting from the lower variable transportation costs, some scenarios including rail transportation suggest biomass can occur from distributed biomass supply areas that have low biomass production costs.

The spatial patterns of the biomass supply chain configurations vary for the systems aiming to support the ethanol demands in Los Angeles, California and Chicago, Illinois. Because of high *Miscanthus* yield and low land opportunity costs, the unit production costs of *Miscanthus* are lower in southern Illinois. To meet the California ethanol demand, the difference in transportation distance across Illinois are not significant. Therefore, biomass procurement costs are the critical factor. Most scenarios select southern Illinois for biomass supplies. By contrast, Chicago is located in the northeastern part of Illinois, and therefore, the trade-off of ethanol transportation costs and biomass procurement costs are significant. The optimal supply chain configurations shift to central and northern Illinois to reduce transportation costs.

Discussion

Investigating how to design an efficient and effective biomass supply chain is critical to facilitate large-scale biofuel development. This work provides an overview of various biomass formats and transportation modes, identifies the interactions between biomass formats and transportation cost estimation, and evaluates the systems performance of large-scale biomass–biofuel supply chain configurations. Comparing various biomass formats to commodities such as coal, ethanol, and corn in terms of density, weight and volume limits, and value of goods suggests that long-distance transportation costs for biomass should follow a pattern similar to coal transportation. The modified BioScope optimization model has been applied to evaluate a four-stage biomass–biofuel supply chain that includes biomass supply, CSP, biorefinery, and ethanol distribution. Fifteen scenarios, a combination of three biomass formats and five supply chain configurations, have been evaluated using biomass produced in Illinois to meet biofuel demands in both California and Illinois. The results showed that converting biomass to ethanol locally and shipping ethanol for long-distance is optimal. This configuration is similar to the existing corn-based ethanol production and distribution system. Highly densified biomass outperforms other types of biomass for long-distance movement, although it is not suggested to support local biorefining.

The model optimizes facility capacity and location to balance the trade-off between facility economies of scale and transportation costs. The current annual system demand is 200 million gallons. Assuming a conversion rate of 80 gal Mg^{-1} of cellulosic biomass, the system demands 2 500 000 Mg of biomass per year. The model results suggest to build a single centralized cellulosic-ethanol biorefinery to capture the economies of scale in all scenarios. This indicates that the economies of scale of biorefinery have a higher impact on the system costs than preprocessing technology and transportation mode.

For comparison, current corn–ethanol dry grind facilities have an average ethanol production capacity of 100 million gallons per year. Given a corn–ethanol conversion rate at approximately 100 gal Mg^{-1} of feedstock, the average throughput rate for corn–ethanol facilities is approximately 1 000 000 Mg per year. The proposed cellulosic-ethanol facility capacity in the current study is more than twice as large as the average capacity of existing corn–ethanol facilities. This indicates that the economies of scale are critical for the success of cellulosic-ethanol production.

Considering the case study of Illinois–California biomass–biofuel supply chain, moving ethanol long distance is \$0.24 gal^{-1} lower than moving biomass long distance. Given the magnitude of this cost difference, it can be foreseen that state policies or incentive plans could affect the design of the biomass–biofuel supply chain. For example, if a state government proposes additional incentives to promote local biorefining industry development, building a biorefinery near the demand area and sourcing biomass feedstock long distance from other states might become more economical for producers relative to purchasing biofuels from other states. The cost of building a biorefinery is assumed constant for the two regions in this study, which ignores the difference in land costs, policies, taxes, and other economic factors. It is possible that local incentives would be available for building a commercial cellulosic-ethanol facility, and this would potentially reduce the cost estimation of facility related costs in this study.

In addition to biomass supply chain management, biomass–biofuel conversion efficiency is critical for the success of cellulosic-ethanol commercial production. Feedstock particle size has been evaluated to affect the ethanol conversion efficiency (Vidal *et al*., 2011). In this study, we assume all three biomass formats have the same conversion rate at 80 gal Mg^{-1} of biomass. It is possible that highly densified biomass may improve the conversion efficiency as a result of finer particle sizes and increased reaction surfaces, which would affect the total system performance and technology selection decisions. Through data share and collaborations with other research groups, the developed modeling capability is well positioned to conduct scenario and uncertainty analysis on different biomass preprocessing and conversion technologies, enabling concurrent science, engineering, and technology decision support.

Acknowledgement

The study was funded by the Energy Biosciences Institute.

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