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Opportunities and Challenges in the Design and Analysis of Biomass Supply Chains

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Abstract The biomass supply chain is one of the most critical elements of large-scale bioenergy production and in many cases a key barrier for procuring initial funding for new developments on specific energy crops. Most productions rely on complex transforming chains linked to feed and food markets. The term 'supply chain' covers various aspects from cultivation and harvesting of the biomass, to treatment, transportation, and storage. After energy conversion, the product must be delivered to final consumption, whether it is in the form of electricity, heat, or more tangible products, such as pellets and biofuels. Effective supply chains are of utmost importance for bioenergy production, as biomass tends to possess challenging seasonal production cycles and low mass, energy and bulk densities. Additionally, the demand for final products is often also dispersed, further complicating the supply chain. The goal of this paper is to introduce key components of biomass supply chains, examples of related modeling applications, and if/how they address aspects related to environmental metrics and management. The paper will introduce a concept of integrated supply systems for sustainable biomass trade and the factors influencing the bioenergy supply chain landscape, including models that can be used to investigate the factors. The paper will also cover various aspects of transportation logistics, ranging from alternative modal and multi-modal alternatives to introduction of support tools for transportation analysis. Finally gaps and challenges in supply chain research are identified and used to outline research recommendations for the future direction in this area of study.

Keywords Bioenergy · Supply chain · Transportation · Logistics · Sustainability · Pan American

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Introduction

During the last decade, we have seen an increase in the use of bioenergy (including biofuels) all over the Pan American region that is produced from various types of biomass feedstock. In several countries mandatory blends with fixed or variable share of biofuel, or other forms of promotions, are already in place. As a consequence, a new industry was born primarily reliant on well-established agricultural product transforming chains.

As an example, in the United States (US), the projection of replacing 30 % of gasoline consumption by 2030 (EPA 2014) will require the processing of more than a billion tons of biomass on an annual basis (US DOE 2011). That level of production would require significant infrastructure investments over the next decades. Current corn-based biorefineries in the US have a median size of about 189 million liters (50 million gallons) per year with the largest of them producing over 757 million liters (200 million gallons) per year (RFA 2014). Cellulosic-based facilities with similar production levels would consume between 0.6 and 2.4 million dry tons of biomass annually, based on the US DOE 2012 study default of 321 L (85 gallons) per dry ton. Processing a billion tons annually with plants in this size range would require between 417 and 1667 bio-refineries. Most of the large-scale production of liquid biofuels relies on complex transforming chains linked to feed and food markets, and in many cases (such as corn or soybeans), the biofuel component is very small in volume or mass compared with the food/feed product. An important factor in these cases is the possibility of supporting shifts between final products without affecting the whole production of the crop, transport, etc. (Hilbert et al. 2014). This type of shift in the biofuel product may be caused by a change in relative prices or restrictions due to policy changes in domestic and overseas markets and has already occurred in certain significant markets, such as the Brazilian bioethanol from sugarcane and the Argentine biodiesel from soybeans.

Large-scale facilities also require even longer and more complex supply chains to bring in more biomass and to distribute the biofuel to consumers. The development of this infrastructure over the next 15 years can only be achieved through effective supply chain management, but supply chains for bioenergy feedstocks are more complex than those for most other industrial feedstocks. The many stakeholders involved in bioenergy development result in multiple, sometimes conflicting, objectives for feedstock value chains, including minimizing cost and/or environmental impacts, stimulating rural economies, maintaining quality, and supplying adequate volumes year round. The complexity of the chains and the large number of stakeholders make the design of supply chains an integral part of the overall biofuels industry development, and inadequate designs may not be economically, environmentally, and socially sustainable.

The remainder of the paper comprises five sections. The first section introduces the specific steps of the biomass supply chains, followed by a section describing a concept of integrated landscape management and advanced supply chain systems for sustainable biomass production. The next part will introduce modeling tools developed to analyze the different components of biomass supply chains, including a separate section that concentrates on transportation logistics, one of the key components in the overall supply chain. Transportation aspects are followed by description of a comprehensive supply chain model that uses information from previous tools to evaluate cost, production, and distribution tradeoffs across the entire network. The final section identifies key gaps in current knowledge and provides recommendations for future research and for system designs, models, and related analysis to biomass supply chains.

Biomass Supply Chains

As the bioenergy industry expands from a primarily sugar- or starch-based system to a cellulosic-based system, new infrastructure will need to be developed across the countries. The corn starch-based ethanol system can rely on a well-established logistics process for harvesting, transporting, and storing corn, but many of the feedstocks for the cellulosic process do not have such a robust logistics support framework. The new specific energy crops are also more susceptible to market changes since alternative demands for the product are limited or do not exist. While the specific details and markets of every biomass supply chain are different, their supply chains include a common set of components, as presented in Fig. 1.

Biomass cultivation activities may need to take place, if a feedstock requires planting or other regular maintenance, such as fertilizer application, thinning, or irrigation. Some feedstocks, such as algae, require intense cultivation procedures that may lead to significant economic and environmental burdens (ANL et al. 2012; Handler et al. 2012) while naturally regenerating feedstocks, such as native forest biomass, may not require these activities.

Most biomass feedstocks will require *harvesting* in order to remove biomass from the growing landscape and consolidate it for further use. Harvesting activities, like most agricultural activities, appear to consistently be moving toward high input, high yield processes that are heavily mechanized (e.g., Abbas et al. 2013). In cases where the biomass feedstock can also serve as an agricultural crop, harvesting systems simply mimic the current practices for that crop. In cases where agricultural residues are utilized as a biomass feedstock, novel systems may be developed to harvest the residual part of the plant along with the commodity agricultural portion, or a second pass may be required to remove residues after primary harvesting is completed.

Biomass transportation can be a significant component of the overall product cost and energy use. Careful planning and coordination is required to optimize the movement of a low-density, low-cost, widely dispersed feedstock to one or more processing. Present commercial crops have the advantage that co-products and by-products are responsible for covering a significant portion of production cost, and the biomass and biofuels can use this advantage to lower costs and energy consumption. Depending on the travel distances and the local infrastructure, it may be possible to achieve cost savings through the use of multiple transportation modes (e.g., truck, rail), but this will depend on the specifics of the feedstock origins, processing destinations, and other local conditions, such as infrastructure availability.

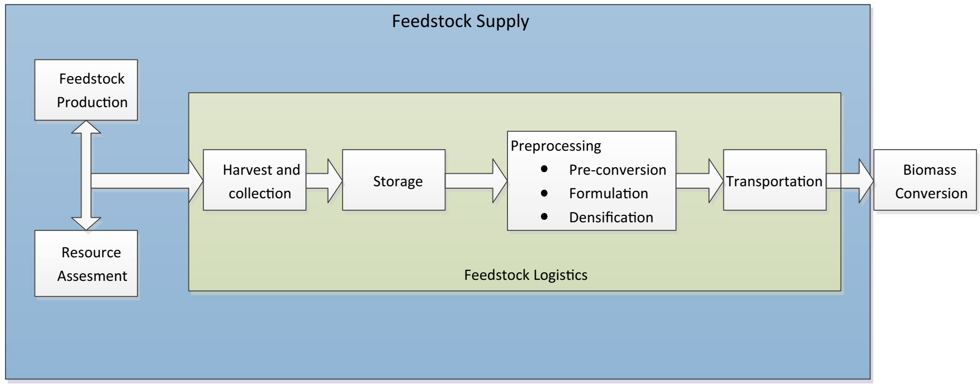

Fig. 1 Biomass supply chain components. Source: US DOE (2012)

Biomass storage capability is a necessary component of the supply chain at certain points (post-harvest, between transport modes, prior to processing). While this may add costs or time delays to the supply chain, biomass storage offers advantages that can outweigh the negative aspects, such as reducing moisture content, providing access to multiple transport modes, and developing a reliable supply of biomass to maximize the use of processing capacity.

Biomass processing may take several forms—the feedstock may be integrated, but may also need to be separated into components (seed oil and seed meal) which are processed in the same location with different processing plans. Further size reduction or physical processing (e.g., drying) may need to take place before conversion into heat/power. Biofuel production pathways are constantly developing and may rely on biological mechanisms such as fermentation, or thermochemical pathways such as pyrolysis. Each technology will be best paired to a set of feedstocks most suited to the processing pathway, but some promising technologies such as catalytic hydrothermal gasification (CHG) may offer the ability to process a wide range of biomass feedstocks (Elliott et al. 2009). After processing, the *product storage and final transport* stages are often less complex in nature due to the stability and energy-dense nature of the products. Bioenergy products can be used locally for heating sources, via the electrical grid, or via transportation system for liquefied products.

Designing Sustainable Biomass Supply Chains

Designing biomass supply chains with economic and environmental metrics in mind provides opportunities for reducing product cost while protecting, and even enhancing, the landscape for a broader range of stakeholders (Parish et al. 2012). Specifically, decisions made in selecting and configuring equipment for harvest, transportation, storage, and processing impact a number of environmental sustainability indicators outlined by McBride et al. (2011) relating to soil quality, water quality, and greenhouse gases. Here we will describe how proposed advanced biomass supply chain designs take advantage of integrated landscape strategies developed to minimize environmental impacts while maximizing producer profitability. We will also demonstrate how biomass supply chain models are being developed to evaluate tradeoffs between cost and environmental impacts.

Advanced Supply Systems for Coupling Sustainable Bioenergy Land Use to Biomass Trade

Large-scale bioenergy development will shift current land use dynamics in the agricultural sector. The establishment of biofuel and biopower feedstock markets has great potential for encouraging more sustainable land use practices (Bonner et al. 2014; Pratt et al. 2014; Muth et al. 2012). Work has been done showing that the strategic integration of food, feed, fiber, and fuel crops onto landscapes can create more sustainable and more productive agricultural systems (Lee et al. 1992; Scherr and McNeely 2008; Douglas and David 2013). Integrated landscape management could contribute to a sustainable solution for biomass trade, as it increases total biomass production, improves environmental performance, and has the potential to improve economic performance. Although integrated landscape management can create more sustainable land practices, the implementation challenge is that existing lignocellulosic biomass supply and trading systems cannot feasibly handle diverse crops produced in a highly distributed way across the landscape (Hess et al. 2009). Creating a robust biomass trading market that can couple diverse and distributed crops to energy producers requires establishing biomass commodity feedstocks that are stable, dense, flowable, and predictable in their material specifications. This requires advanced supply systems with preprocessing steps to convert raw biomass into a tradable commodity feedstock near the point of production. However, the potential for producing dedicated energy crops alongside agricultural residues is challenged by more than complications in a supply chain. Such transformations rely deeply on political measures, public perception, and market stability (Hilbert et al. 2014). In order for land managers to justify altering their crop production practices to include energy crop production, there must be sufficient certainty in their ability to reliably generate revenue and protect the land's natural resources.

Compared to traditional cropping systems that manage productivity and environmental sustainability on an overall average field scale, integrated landscape management may consider subfield scale variability to substitute row crops with annual or perennial biomass crops (herbaceous or wood) for improved environmental and productive performance. For example, with the integrated landscape management approach, perennial energy crops may be planted in environmentally sensitive portions of a commodity row crop field to protect soil resources by reducing erosion or nutrient loss. Alternatively, areas of a field that typically under-produce and result in lost revenue for the producer may be planted in a biomass crop (such as switchgrass) that is better suited to the productive potential of the soil (Bonner et al. 2014). This approach results in a landscape mosaic simultaneously producing conventional agricultural residues and dedicated energy crops. Successful integrated landscape management produces both economic and environmental benefits to growers, thereby improving the biomass supply–demand dynamics and making more biomass available at lower access costs (CAST 2012). The practice of these integrated landscapes will increase the technical challenges of managing and harvesting multiple biomass types, but the increased total resource should offset these challenges. Figure 2 shows a landscape mosaic where a low diversity large row crop field is transformed to a crop fields with high crop species diversity that uses all the land for production and integrated ecosystem services.

The advanced feedstock supply system incorporates many species and types of biomass that are formatted at specialized preprocessing depots positioned near resource production locations, similar to grain storage elevators (Fig. 3). Typical preprocessing operations at a depot could include particle size reduction, moisture mitigation, densification, and advance process such as blending, partial pretreatment, and even fractionation to oil, sugar, or char intermediate products. Biomass leaves these depots as a commodity feedstock that is stable, dense, flowable, and has a defined grade of material specification. Because preprocessed feedstock is more easily and efficiently transported to the biorefinery (via rail or barge), access to isolated and low yield areas is increased. In other words, biomass resources can now be aggregated to the large scale of energy markets. This increases the volume of material that can cost effectively enter the market.

The advanced supply system has the ability to economically connect feedstock with distant markets. This broadens accessibility by creating regional and national markets, while a conventional supply system is coupled to a limited number of feedstock types and limited to local markets.

Advanced supply systems can handle crop diversity occurring in integrated landscape management and improve the sustainability of integrated landscape design by efficiently coupling the biorefinery and feedstock locations. These supply systems have the ability to connect small quantities of biomass, such as switchgrass, wheatgrass, etc., produced from integrated landscape management with a tradable commodity market.

Modeling Tradeoffs between Costs and Environmental Impacts of Biomass Supply Chains

The planned expansion of biomass production and goals to implement advanced designs to enhance sustainability requires a more robust set of models to evaluate the

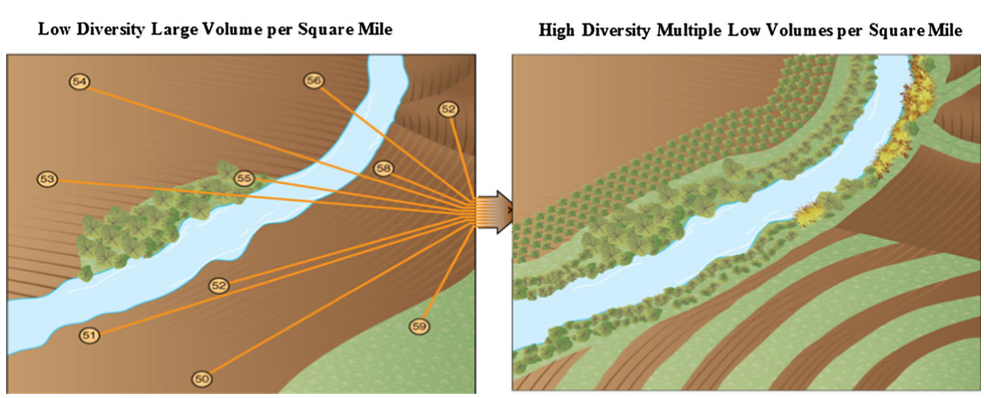

Fig. 2 An integrated landscape management approach optimizes land and soil types to their respective productive use and provides ecosystem services through increased crop diversity. Resource: Authors

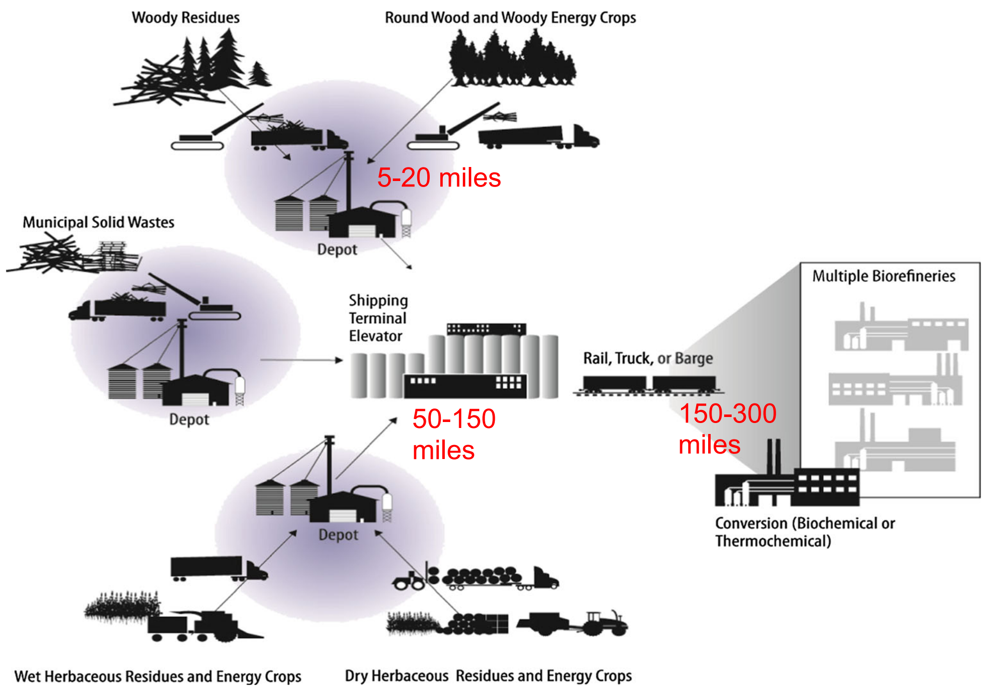

Fig. 3 Advanced supply system based on distributed depots to generate uniform feedstock 'commodities'. Source: Authors

tradeoffs between sometimes competing objectives to minimize product cost while avoiding negative environmental impacts. In recent years, biomass supply chain models have become effective tools in exploring the complex interactions between crop production, harvest, storage, transportation, preprocessing, and final distribution (Mafakheri and Nasiri 2014; Yue et al. 2014). Some of the fundamental questions that can be explored using biomass supply chain models include:

- What will be the landscape of this new energy production process?
- What cost factors influence the decisions on size and number of refineries?
- What are the optimal configurations of biomass production, harvest, preprocessing facilities, refineries, transportation, and distribution systems to achieve cost and quantity targets while minimizing environmental impacts?
- Can we predict where these facilities are likely to be built and how this impacts transportation cost, infrastructure needs, and fossil fuel use?
- What are the economic and social tradeoffs in the process that will drive the topology of the supply chains?
- What is the final product price that will provide desirable returns to feedstock suppliers, considering logistics and processing costs?
- Which other products could be derived from the harvested biomass?
- How could the combination of volumes and prices of different products increase farm income per hectare?

In the US, two modeling tools have been recently developed by the Oak Ridge National Laboratory (ORNL) to address many of these questions. The Integrated Biomass Supply Analysis and Logistics (IBSAL) model simulates biomass movements from harvest to delivery to the conversion reactor to compare the costs and energy use of various supply chain scenarios. Biofuel Infrastructure, Logistics, and Transportation (BILT), described later in the paper, is an optimization model that analyzes facility location options, transportation routes, and processing costs from field to consumer to minimize total cost. Internationally, other supply chain-related models exist, such as the Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM) developed by the Food and Agriculture Organization of the United Nations (FAO) which can be used to produce supply and demand balance mapping for biomass studies.

Integrated Biomass Supply Analysis and Logistics (IBSAL) model

The IBSAL model combines discrete-event and continuous modeling techniques in ExtendSim software (Imagine That, Inc.) to simulate biomass movement through the supply chain (Sokhansanj et al. 2006, 2008). It has been successfully used for simulation of agricultural residues (Ebadian et al. 2014, 2011; Sokhansanj et al. 2010; Stephen et al. 2010), perennial grasses (Kumar and Sokhansanj 2007; Sokhansanj et al. 2009), and forest resources (Mahmoudi et al. 2009; Mobini et al. 2011) for bioenergy. In IBSAL, biomass "items" flow to modules which represent harvest, storage, preprocessing, or transportation operations (Fig. 4). A particular strength of IBSAL is its representation of not only the mechanical operations performed on biomass, but also characterization of the impacts of processes, such as drying and rewetting while biomass is lying in the field and dry matter loss during storage. These processes are often neglected in supply chain models though they have significant impact on harvest decisions and on the downstream processing costs associated with achieving quality specifications. As the model runs (daily time step), parameter values are read from an Excel spreadsheet which serves as a way for users to modify input data. This construct has proven to be useful for sharing models with those who do not have programming experience.

The first IBSAL module defines the biomass production region by setting parameter values such as yield, number of farms to include in the simulation, farm size, biorefinery annual demand, harvest schedule (fraction of biomass harvested per week), harvest moisture content, etc. From this setup module, biomass passes through the operational modules. The machinery of each operational module varies with crop and supply chain design. Within a module, the cost per unit of dry biomass ($/Mg) is determined by dividing the hourly machine cost by throughput (estimated based on user-specified parameters). The cost ($/h) to operate machines (including truck or tractor for non-powered equipment) is calculated in the Excel sheet following the methodology by Turhollow et al. (2009). Storage modules operate a bit differently with storage cost estimated based on the required storage footprint (ft^2) and the cost per unit area ($\$/ft^2$). Loading biomass into and out of storage is considered a separate operation from storage itself and is handled in a module that operates like the other equipment modules. Energy consumption and the associated GHG emissions from fuel use are also calculated by IBSAL.

IBSAL simulation models are useful in performing experiments on supply chain designs and in guiding field trials. One example shown here is comparing the costs of varying stover removal rates. Corn stover has significant potential as a biofuel feedstock, but excessive removal can have detrimental effects on soil health by removing critical soil organic carbon and increasing erosion potential (Birrell et al. 2014). Johnson et al. (2014) reported that based on field observations (in Iowa, South Carolina, Pennsylvania, and Indiana) and published research literature, the range of minimum stover return rates needed to maintain soil organic carbon was 5.74 ± 2.4 Mg ha^{-1} $year^{-1}$. Given the high standard error of these estimates, the authors

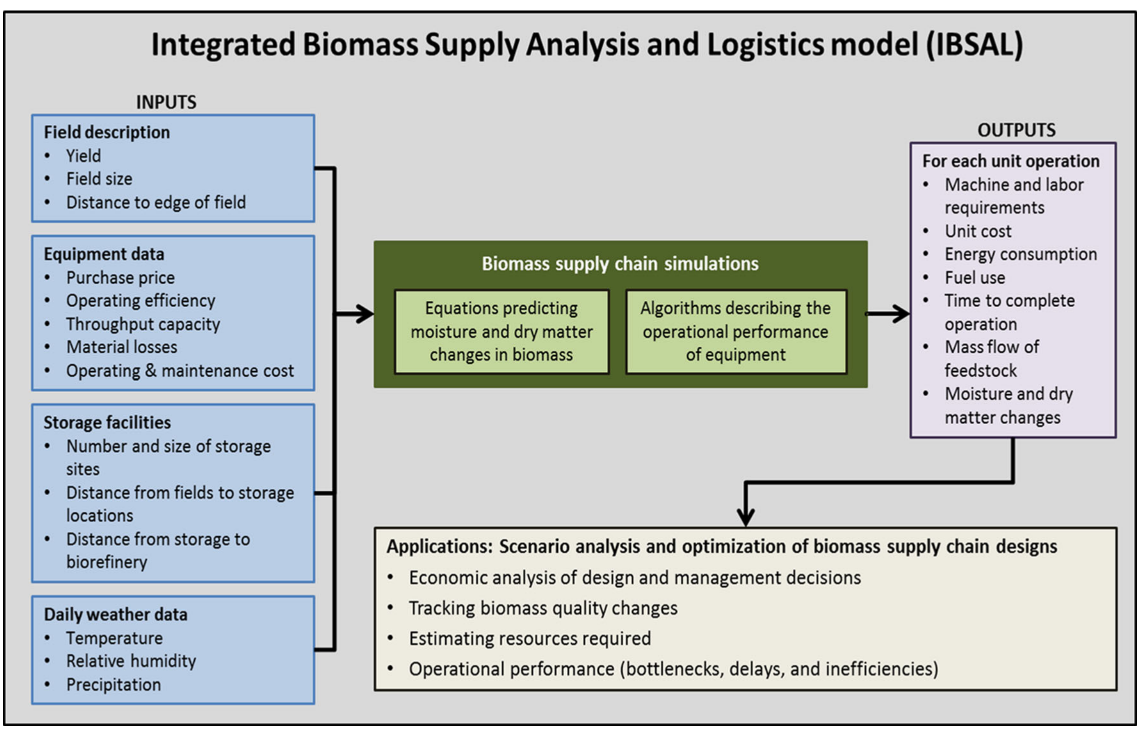

Fig. 4 Overall structure of the IBSAL model. Source: Authors

cautioned that field-specific stover removal decisions should be based on field, or even subfield, level soil conditions. To evaluate how this range of stover removal affects harvest cost, an IBSAL simulation of a stover round baling operation was run for a range of removal rates, as shown in Fig. 5. Baling cost decreased 50 % from $18.50 to $9/dry Mg when stover removal was increased from a sustainable 1.69–5.91 dry Mg/ha.

For all biomass supply chain models, data quality is a significant challenge. In many cases, the analysis being performed has not been field tested at a large enough scale to collect performance data and collection of such data is costly and time-consuming. To demonstrate the impact of data quality, a simple sensitivity analysis of baler field speed and field efficiency was performed on an IBSAL corn stover harvest model. The model simulates collection of stover by a large square baler following grain harvest. The stover is allowed to dry in the field to a moisture content considered safe for baling. As shown in Table 1, increasing field speed from the baseline value of 3.2–12.8 km/h decreased the total baling cost and CO_2 emissions by 37 and 49 %, respectively. Increasing field efficiency from the baseline value of 0.65–0.9 decreased the baling cost by 21 % and CO_2 emissions by 27 %. As the ranges of field speed and field efficiency for a large rectangular baler are 3.2–12.8 km/h and 0.7–0.9, respectively (ASABE 2011), it is reasonable to expect that such variations in speed can occur between fields and possibly within a field. Selecting a value for field speed based on a single observation can, and likely often does, result in errors in estimating bioenergy feedstock costs and environmental impact metrics. Where data are available, a better approach is to run the model for a range of observed machine performance parameters.

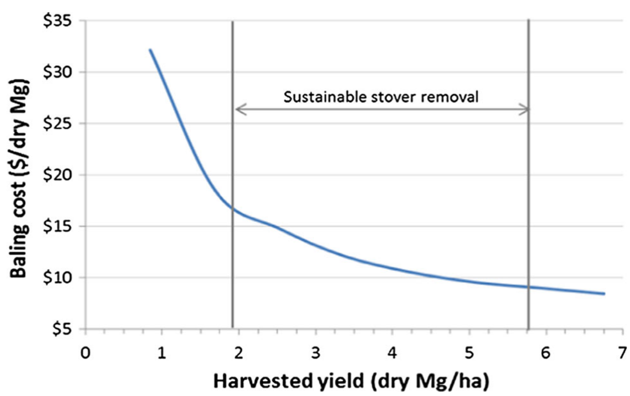

Fig. 5 An IBSAL simulation of a stover round baling operation in Iowa was performed to assess the cost implications of varying stover removal rates to protect soil organic carbon. Source: Authors

Table 1 Sensitivity analysis of baler field speed and field efficiency in an IBSAL corn stover harvest model

	Baler cost ($/Mg)	Tractor cost ($/Mg)	Total baling cost ($/Mg)	CO_2 emissions from fuel use (kg CO_2/Mg)
Speed (km/h)				
3.2	$13.77	$16.33	$30.10	16.1
6.4	*$9.10*	*$8.17*	*$17.27*	*8.0*
9.6	$7.54	$5.45	$12.99	5.4
12.8	$6.76	$4.08	$10.84	4.0
Field efficiency				
0.65	*$9.10*	*$8.17*	*$17.27*	*8.0*
0.75	$8.48	$7.08	$15.56	7.0
0.85	$7.99	$6.24	$14.23	6.2
0.9	$7.79	$5.90	$13.69	5.8

Source: Authors

Italics indicate baseline scenario

Woodfuel Integrated Supply/Demand Overview Mapping (WISDOM)

As another example of biomass supply chain modeling, the WISDOM method has been applied for biomass studies in several countries around the world (WISDOM 2014). Argentina, in particular, developed a national study including all types of biomass. In the Argentinian case, the methodology was enlarged to include residues from the agricultural and agro-industrial sectors. The methodology could be summarized in a scheme presented in Fig. 6.

The study in Argentina covered several sources of biomass over the whole territory. Specific calculations were performed to estimate the biomass availability in each transforming chain, and local studies were done taking into consideration the roads and logistics concerns. Based on commercial balance surplus, an example of bio-shed analysis was carried out for the city of Cordoba considering minimum, medium, and maximum productivity levels (Fig. 7) (Drigo et al. 2009).

Transportation—A Key Component of Biomass Supply Chains

Regardless of the model or the analysis approach used, transportation and related logistics is recognized as one of the key components of supply chains. In the biomass industry, the role of transportation varies greatly, but especially for feedstock, it is often considered a competitive, low-margin business, as the inherent features often result in a low-efficiency enterprise (Mendell and Haber 2006). These features include a large number of points of origin for loads with limited access, low product density,

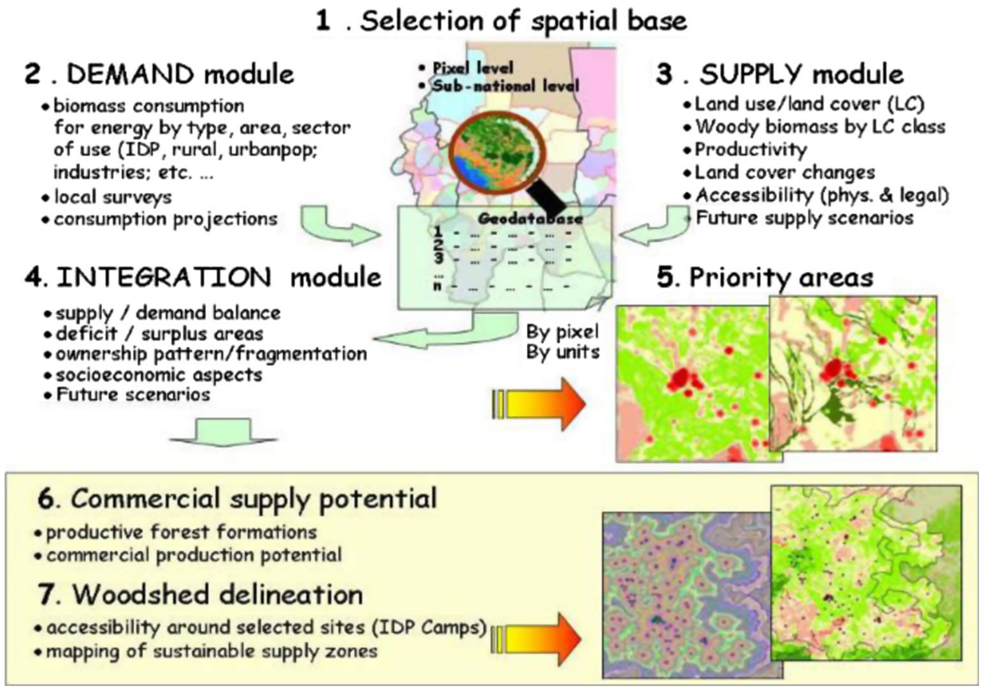

Fig. 6 Description of WISDOM method. Source: Drigo et al. 2009

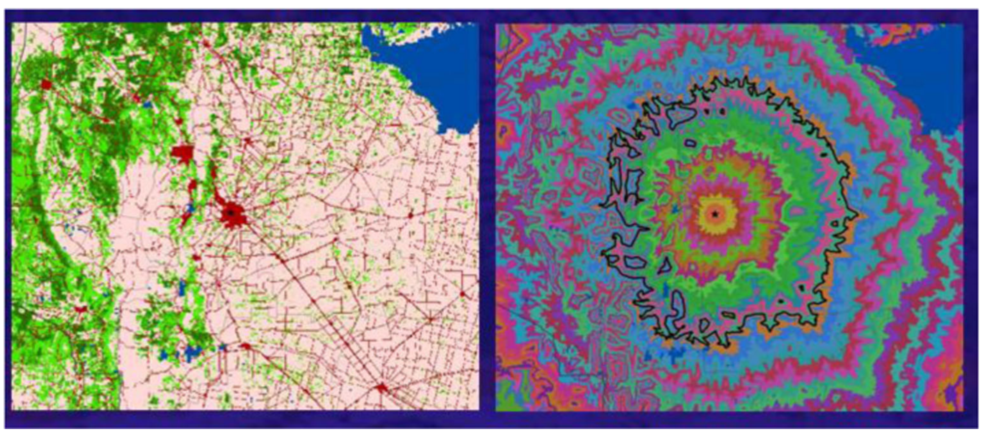

Fig. 7 Road maps and final output of biomass supply areas for the province of Cordoba Argentina. Source: Drigo et al. (2009)

often specialized equipment decreasing opportunities for product backhauls, and a significant portion of operating hours spent loading and unloading the product (e.g., Carlsson and Ronnqvist 2007).

While truck, rail, and water can all be used for moving biomass and final products, the literature reveals the dominance of trucks as the primary mode for transportation (McDonald et al. 2001; Forest Resources Association 2006; NACD 2008; Wojnar 2010). Truck movements are most commonly handle origin to the final destination (mill or plant) in a single movement, while rail and water commonly require a truck drayage at least in one end of the trip (Schroeder et al. 2007). In general comparison, truck and water tend to trade places as the best/worst performer for most criteria, while rail performance is somewhere in between (Table 2).

Multi-modal Transportation

Using two or more modes of transport for a freight movement is a regular practice (Lowe 2005). There are various definitions for the practice, such as multi-modal transport, combined transport, and intermodal transport, but the overall objective is always an integrated transport network, where each mode of transport is expected to be used at its best scale and operation (Reis et al. 2013).

Decision Criteria for Modal Selection

In 1984, Bjorn divided factors behind a user's choice of freight transportation into two perspectives: rational and non-rational (Bjorn 1984). The rational factors include cost, performance, and quality factors, such as speed and

Table 2 General comparison of transportation modes

Criteria	Truck	Rail	Water
Network coverage	High	Medium	Low
Accessibility	High	Medium	Low
Fixed cost	Low	Medium	High
Variable cost	High	Medium	Low
Energy efficiency	Low	Medium	High
Capacity per unit	Low	Medium	High
Speed and flexibility	High	Medium	Low

Source: Authors

tracking services, while the non-rational factors contain personal attitudes, relations, and traditions of the company. As the data analysis and tools have improved, along with deregulation of freight transport market and intensifying competition among modes, the importance of rational factors in decision making has increased, leading the current freight transport users to select the mode which provides the topmost utility value. (Choi 2009) A review of multi-modal transportation optimization studies reveals that cost, time, and routing were the most common objectives for the optimization exercise, while environmental metrics, such as emissions, were left to a smaller or negligible role. In biomass research, two recent examples of this include Lin et al. (2014) who tried to minimize annual biomass–ethanol production costs by optimizing both strategic and tactical planning decisions simultaneously, and Sharma et al. (2013) who developed a scenario optimization model to minimize the cost of biomass supply to a biorefinery, considering harvest, transportation, and storage costs.

The high proportion of transportation cost of delivered biomass or bioproduct makes it one of the most important criteria in supply chain optimization (Wolfsmayr and Rauch 2013). Transportation cost is typically divided into fixed costs and variable costs, based on distance and/or time (Gronalt and Rauch 2007). For truck transportation, the cost is often described as a linear function based on distance with negligible fixed costs, while for rail, water, and multi-modal transportation, fixed and intermediate handling/storage account for significant percentage of total cost. Figure 10 presents an example of the effects of different unit costs and handling costs to the cost efficiency of a multi-modal transportation chain. In this Figure, the cost of multi-modal (truck/rail) transportation is compared to single-mode truck transportation from origin (O) to final destination (F), using the length of rail haul as a variable. The product is transloaded to rail after truck drayage in point 1 and either taken to final destination by rail, or transloaded back to truck for final drayage at point 2, 3, or 4. Figure 8 reveals that even though the transport cost (per kilometer) of the rail segment is significantly lower, the added handling cost leads to higher or equal total cost for the multi-modal option, if the load is transferred back to trucks at points 2 or 3, respectively.

In research by Searcy et al. (2007), it was found that rail transport is often more economical than truck for larger quantities of biomass feedstock movements over 300 miles (500 km) and water is more cost-efficient than rail

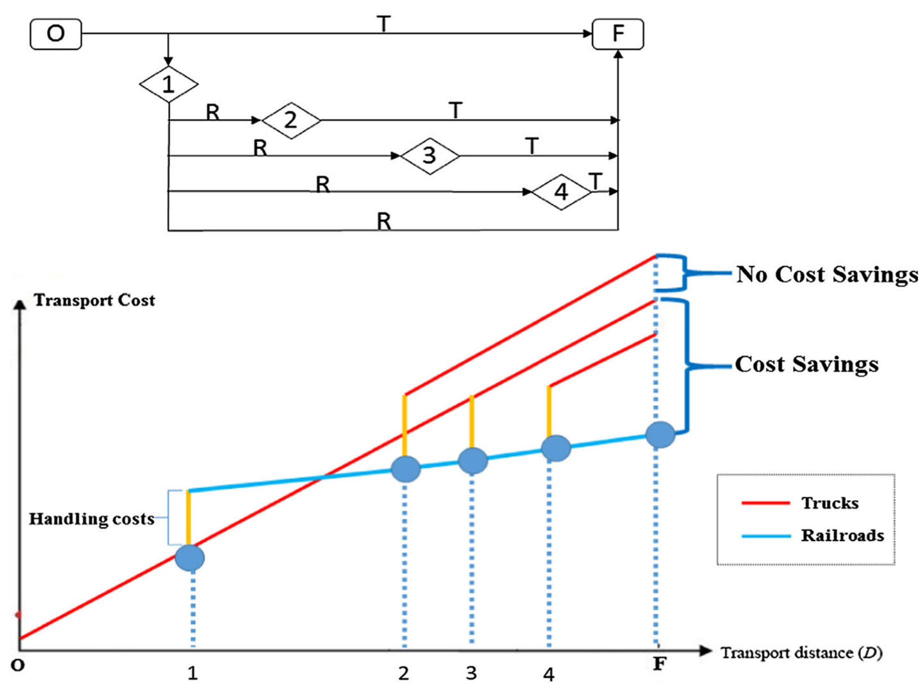

Fig. 8 Multi-modal chain cost efficiency. Source: Authors

Table 3 Ethanol transportation costs, by mode of transportation

	Truck	Rail	Barge
Loading and unloading	$0.005/L	$0.004/L	$0.004/L
Time dependent	$32/h per truckload	Not applicable	Not applicable
Fixed cost	Not applicable	$2.325/L	$0.37/L
Distance dependent	$0.8078/km per truckload	$0.0012/km per 100 L	$0.0025/km per 100 L
Unit capacity	30,283 L/truck	124,918 L/car	4.77 million liters/vessel

Source: Adapted from National Academy of Sciences et al. (2009)

Table 4 Transportation costs for transport modes used in the soybean energy chain (2010)

Cost item	Unit (US$/Ton-km)	Weight (%)	U × W
Truck transport	0.08	84	0.067
Train transport	0.04	15	0.006
Inland ship (barge) transport	0.02	1	0.000
2010 average weighted transport cost estimated	–	–	0.073

Source: Hilbert et al. (2013)

transport after 900 miles (1500 km). However, the type of biomass and availability of facilities can significantly affect the total cost of transport on a case by case basis (Searcy et al. 2007). These dependencies make development of generalized cost formulas difficult, and each scenario should be analyzed individually. The variance of products is smaller for biofuel distribution, so development of general transportation costs has more relevance. Table 3 presents an example of estimated ethanol transportation costs for various modes in North America, and Table 4 provides unit cost tabulation for Argentina, including the weighted value, based on each modes market share. These two tables highlight the differences not only in values, but also in the units used and the general breakdown between transportation cost parameters.

While cost is one of the predominant criteria for modal selection, other important factors should be included in the analysis (Table 5).

In most of the cases, additional criteria (including environmental factors) have not received as much attention as have economic benefits (Ruiz et al. 2013). However, the low energy density of biomass feedstock (when compared to that of fossil fuels) makes environmental emissions from transportation per equivalent energy generated much more significant. The main concentration of transportation-born emissions tends to be in carbon dioxide (CO_2) over NO_x, S, and particle matter (Kurka et al. 2012; Oshita et al. 2011; Fan et al. 2013). There are some studies that considered all system factors when making decisions, such as Kumar et al. (2006), which identified the highest rank of biomass transportation systems based on economic, social, and environmental factors. According to their results, rail transport is the best option for capacity of four million tons per year. Ayoub et al. (2009) also suggested a methodology for designing and evaluating biomass utilization networks considering three optimization criteria; costs, emissions, and energy consumption, and used a genetic algorithm to solve this multi-optimization problem.

Table 5 Criteria for evaluating optimal transportation

Name of criteria group	Criteria
Time of delivery	Time for transportation, time for border crossing, time for customs clearance, exchange rate fluctuation during delivery time
Reliability of transportation	Delay, missed delivery windows, freight safety (loss, damages), availability of transport units, reliability of transport means
Ecological impact	Emission of CO_2, emissions of harmful substances, noise and vibration, accident and disasters from ecological point of view
Transportation risk	Social economic conditions, cooperation between multi-modal transportation networks

Source: Adapted from Kopytov and Abramov (2012) and Lei et al. (2014)

Specialized Equipment for Biomass Transportation

In addition to modal decisions that offer great variations in economies of scale, efficiencies gained through specialized equipment can affect both economic and environmental footprint of transportation. While a great portion of biomass transportation is handled with conventional equipment, specialized equipment offers one alternative for improvements in the overall transportation logistics. Scandinavian countries have been on the forefront of the development, such as the 30-m-long High Capacity Transports (HCT) trucks with 90 ton capacity that were introduced in Sweden in 2009 (Prinz et al. 2013) and the specialized truck-trailer combinations to maximize the volume and density of residue and stump transport in Finland (Stewart et al. 2010) (Fig. 9). Rail transportation has also seen a recent equipment innovation in the United Kingdom, where a company revealed a specialized pellet car with a larger cubic capacity than anything else currently operated on the UK rail network (Portz 2013).

Intermodal (Containerized) Options

Biomass transportation tends to be most economical, when large volumes of high density materials are transported in a single shipment. Methods, such as advanced supply systems, are geared toward taking advantage of those transportation benefits, but for regions or feedstocks that cannot benefit from such systems, intermodal (containerized) transportation offers an interesting alternative. Intermodal has been at the forefront of latest developments in transportation and there has been 50 % increase in the intermodal transportation loadings since 2000 in North America only (IANA 2014), but the current share of containers in biomass logistics is limited. The advantage of containers is that the biomass can be transported over long distances on road, rail, or waterway, without intermediate unloading and reloading, but container logistics faces challenges. The biggest concern is that containers are too expensive for light bulk commodities such as biomass. An international market study by biomass experts (Laitinen 2013) indicated that while the majority of respondents expected the use of containers in biomass transportation to grow, containers would need to meet the criteria of proper price, high level of confidence on expected cost savings, and good potential to integrate them with current system. One way to avoid high investment cost is container rental which has received attention among the industry (Laitinen 2012). Such business for biomass transportation already exists in Europe. For example, an Austrian company, Innofreight, provides metal container systems, which can be tailored according to customer needs.

In cold climates, such as parts of North America, another obstacle is cold weather, as biomass tends to freeze into metal containers in low temperatures. Lappeenranta University of Technology (LUT) in Finland has studied the possibilities of new lightweight containers to increase the payload and lower transportation costs. The Finnish innovation, a composite container, is only half the weight of a traditional metal container and is made of special channel composite structure, which makes it lightweight and durable, with good weather and corrosion resistance to reduce the freezing problems (Föhr et al. 2013). However, the biomass industry has been unprepared to invest in composite containers and needs more positive user experiences of containers to make the purchase decision (Laitinen 2012).

Transportation Logistics Tools: Multi-modal Log Transportation Model and LabTrans Software

Similar to supply chains, various models and tools have been developed to assist in the transportation logistics. The following sections provide examples of two such tools, Multi-modal Log Transportation Model, developed by the Michigan Technological University, and specialized tools developed by LabTrans in Brazil.

Multi-modal Transport of Logs and the Effects of Changing Fuel Prices

As part of a study to evaluate the price-optimal use of truck and rail transportation for roundwood logs in the Upper Midwest region of the US, Michigan Technological University developed a regional modeling tool to compare the cost of truck transportation with multi-modal (truck/

Fig. 9 Loose residue/stump truck and trailer in Finland. Source: Authors

rail) option. Most logs in the region are either trucked directly to the destination (mill), or trucked to a rail siding and loaded to railcars for a direct movement to final destination. The model, developed in ArcGis and Visual Basic, used loop optimization logic to investigate a dataset of 100,000 actual industry truck trips. The study objective was to find the route and modal combination that yields the lowest total transportation rate between an origin and destination, but the model could also be modified to minimize the fuel consumption or emissions (Lautala et al. 2011).

The research utilized formulas developed from actual log truck rates and publicly posted rail tariff rates. For each rail loading location, a bi-modal compound rate was developed by adding the truck segment rate from the forest to rail siding to the rail segment rate. Intermediate storage was not included, but logs were rather loaded directly from trucks to waiting rail cars. The modeling results suggested that 22 % of the total tonnage should have used the multi-modal option, leading to 3.75 % cost savings ($0.45 per ton or $1.06 a cord, respectively) for the optimized routing and mode choice (Table 6). The sensitivity analysis showed a linear relationship between the fuel price and modal choice, where each dollar per gallon increase in fuel price warranted an additional 7 % of total tonnage to be shifted to multi-modal option. A future study is planned to evaluate the effects of modal choices in overall fuel consumption and emissions.

In another application, the same model was used to develop "cost gradient" maps to represent the cost-efficient supply radius for a planned cellulosic ethanol plant (Lautala et al. 2012). Figure 10 presents three maps, where feedstock transportation cost to the facility is analyzed for three different fuel prices. It can be seen from the figure that the cost-efficient supply radius increases in those areas with nearby rail access (rail lines presented in black). The difference is even clearer for higher fuel prices. The results are also important from an environmental perspective, since rail transportation is known to have lower emission factors per ton mile transported, so increased rail transportation has the potential to lower the overall emissions from biomass transport.

LabTrans Logistics and Transportation Tools

The Logistics and Transportation Laboratory (LabTrans) of Santa Catarina Federal University, Brazil, was created in 1998 to develop decision-making tools that assist Brazilian companies and government to plan the national macro logistics. The use of LabTrans tools for biomass and bio-product transportation has been limited, so specific examples have not been provided. However, tools such as PrevFretes and SIGTrans offer needed functionality for such analysis.

PrevFretes, Freight Forecasting Model

PrevFretes offers the potential for analysis of various fuel (including biofuel) and petroleum byproduct movements by roadway, railway, and waterway from an economical perspective. It is a GIS-based decision support tool to provide up to a 5-year forecast of the cost of transportation. The freight market value and the forecasts can be developed from two perspectives, from the pure cost of transportation, or from the prices practiced in the marketplace that account for transportation profit. The information engendered is essential for making strategic decisions, such as the negotiation of contracts with carriers/logistic operators, as well as for studies investigating the location of future installations, such as refineries and distribution bases.

The system enables users to simulate the countrywide freight projections for fuel and bio-products, distinguishing between transfer and distribution freight. It is also possible

Table 6 Optimization results fuel price $0.76/L ($2.89/gallon, average 2007)

Mode	Ton-Km	Tons	Avg trip Km	Total cost	Avg cost/Ton
Non-optimized					
Single-mode trip: truck	455,250,862.33	3,171,611.15	143.53	$37,912,725.50	$11.95
Optimized					
Single-mode trip: truck	331,847,596.78	2,675,989.03	124.01	$29,004,106.67	
Bi-modal trip: rail segment	100,633,945.06	495,622.12	203.05	$3,199,767.83	
Bi-modal trip: truck segment	22,769,320.50	495,622.12	45.95	$4,287,556.68	
Total cost				$36,491,431.17	$11.51
$ 11.51	354,616,917.26	3,171,611.15	111.81		
Savings				$1,421,294.33	$0.45
Savings percent				3.75%	

Source: Lautala et al. 2011

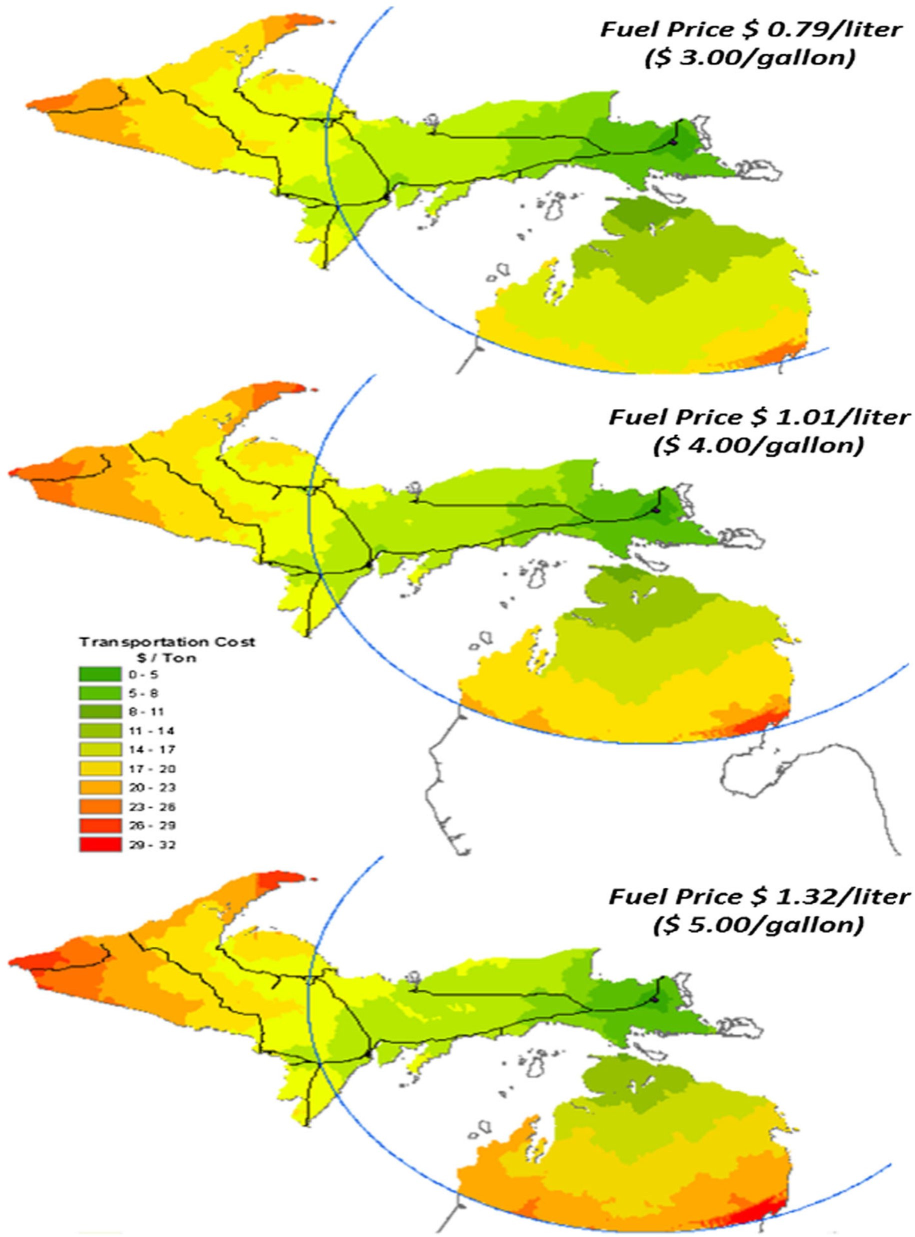

Fig. 10 Transportation cost gradient maps with fuel prices of $0.79, $1.01, and $1.32 per liter ($3.00, $4.00, and $5.00 per gallon). **Blue circles* indicate 150 miles (241 km) distance from proposed facility. Source: Lautala et al. (2011) (Color figure online)

to use the graphic analyses to investigate the relationships between profit margins practiced by the transport companies and the impact of the fixed and variable costs on the transportation system (Fig. 11).

SIGTrans

SIGTrans is a GIS-based decision-making tool capable of performing logistics functionalities, including feasibility analysis and carbon equivalent emissions calculation based on index of CO_2 and N_2O on specific highway segments (Fig. 12). The methodology used considers only CO_2 and N_2O emissions to allow a direct conversion to carbon equivalent. To achieve the benefit of pollutant reduction, it is necessary to compare scenarios, and the effective reduction of carbon emissions must be transformed to monetary terms using the value of the Carbon Trade Exchange. SigTrans uses fleet type, flow of vehicles, and cargo volumes as input and has been used in the past for biomass-related analysis.

Biofuel Infrastructure, Logistics, and Transportation (BILT) Model

The previous sections (IBSAL model and the Transportation Logistics Tools) provide examples of modeling tools applicable to address the details of harvesting and transportation, but the supply chain design must consider

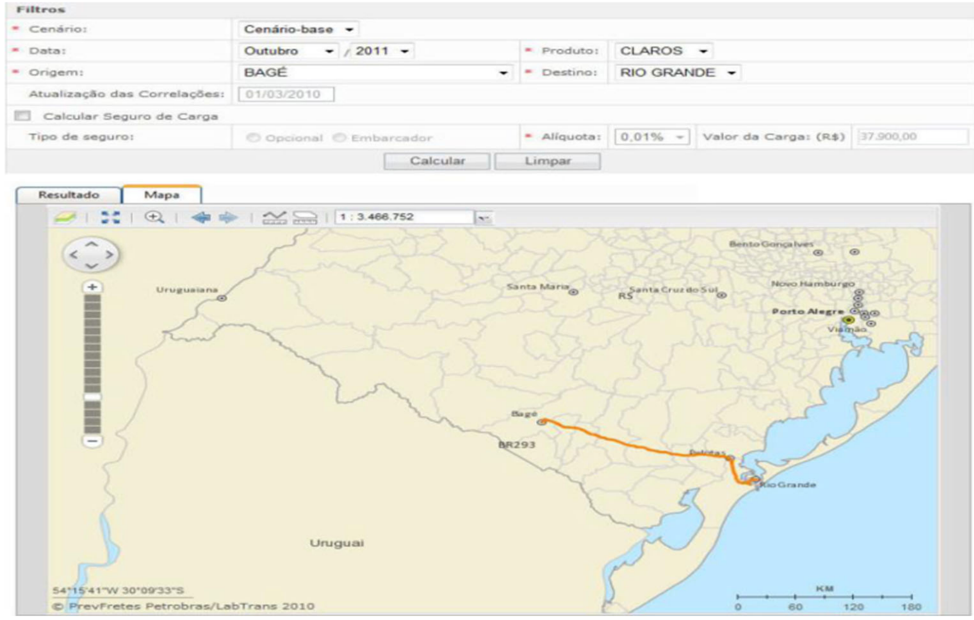

Fig. 11 PrevFretes map with a route for cost and freight market calculation. Source: Authors

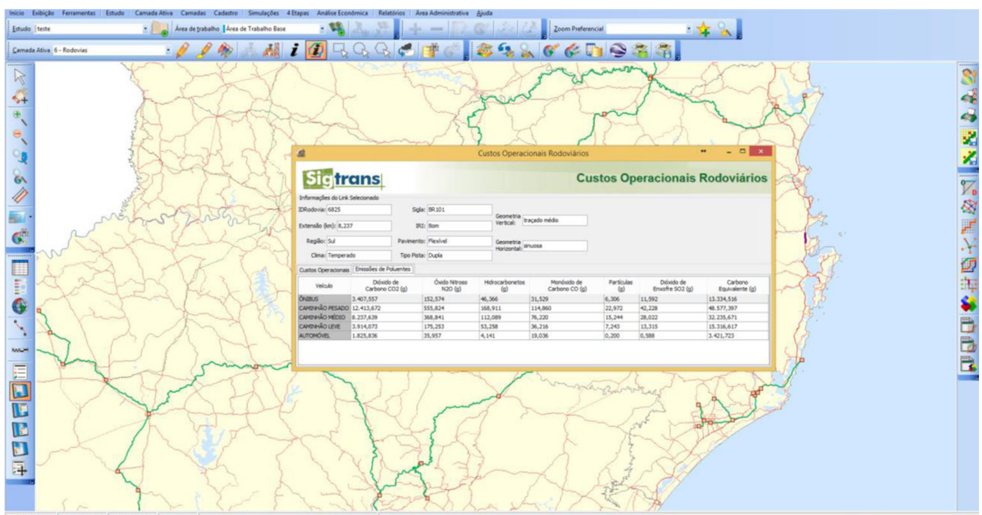

Fig. 12 SIGTrans link's emissions data by vehicles. Source: Authors

comprehensive cost and production tradeoffs across the entire network of production and distribution activities. The goal of the recently established BILT model is to help users (planners, businesses, public) understand the factors influencing the biofuel supply chain landscape—particularly the cost factors. Given a region and a level of biofuel demand—expressed as a percentage of gasoline to be replaced—the model creates a biofuel supply chain for the region that minimizes costs under a given set of assumptions. Currently, the model focuses on liquid fuel production (ethanol), but with appropriate refinery and transportation data the model could incorporate other biochemical and with moderate effort, the BILT framework can be expanded to include by-products and bioenergy. The model considers spatial distribution of biomass to meet the demand (currently at the county level), alternative locations for preprocessing and refinery operations, and existing ethanol blending locations. A major focus of the model is the transportation and logistics of moving biomass from the sources to the refineries, including transportation costs of moving biomass (before and after preprocessing) and ethanol at each link of the supply chain. BILT is supported by data from a variety of studies and sources; in particular, the Billion Ton study (US DOE 2011) data provides supply curves for biomass and transportation costs from studies, such as those described in the Transportation Logistics Tools section above.

The BILT model is implemented as a large mixed integer programming model focused on the following decisions:

Feedstock production Which feedstocks? Where will they be grown/collected? What price will be offered to the farmer? What quantity will be harvested to support each refinery? These decisions are captured by incorporating the supply curves from the updated billion ton study and allowing the model to select from available resources at the county level.

Feedstock logistics How will the biomass be handled, processed, and stored (if necessary) on the farm, in transit and before it is used at the refinery? Will there be intermediary facilities to preprocess, standardize, or densify the biomass prior to the movement to the refinery? These decisions are modeled by allowing the model to "build" depots at locations chosen from a set provided by the user for a specified cost which will transform the biomass into a form suitable for modes with lower transportation costs. The model is flexible, allowing for a landscape mixing refineries using a conventional direct-to-refinery supply and refineries relying on the advanced supply system described earlier in the paper. The model captures the costs of building and operating facilities, including transportation costs, refinery processing costs, and savings associated with preprocessing.

Ethanol production Which biorefinery technologies will be employed? How many refineries of each size will be developed? How much biomass of each type and format will each refinery process? There are still many questions about the development of ethanol refineries. The fundamental questions of chemical processes (biochemical, thermochemical, and gasification), feedstock, feedstock format (bales, ground, and pellets), scale, and location determine fixed and operating costs as well as yields and capacities. The BILT model allows the system to select between multiple potential models of refineries and potential locations. The user defines a set of potential refinery designs by specifying the biomass types to be processed, the yield per ton, the capacity, and the cost for construction and operation (annualized). The model selects which design to construct at each potential location.

Ethanol distribution How will ethanol be moved to blending facilities, and how will it be distributed between the facilities? The transportation networks include the movement of ethanol to the existing tank farms in major metropolitan areas for blending and then to county centroids to simulate satisfying demand. This incorporation of the distribution costs forces the model to balance costs of biomass transport, refinery size and location, and product transport.

The BILT modeling system operates on a set of contiguous US States and an underlying transportation network with a set of locations selected by the user as potential facility locations. The model input is transformed into a standard mathematical programming input file format, MPS, which can then be solved by any standard high-performance solver. CPLEX, Gurobi, and a distributed solver running on a supercomputer (Hartman-Baker 2009) have been used.

To date, the model has been run in two forms for initial evaluation and testing—a full version for researchers to test the general capabilities and a simplified web version for the general community to provide a Beta test. Running the model to optimality can require several hours on a standard desktop, but very good solutions are obtained quickly in most cases. The web implementation took advantage of this observation and provided the user with an optimal solution or the best solution obtained within the first 10 min of calculation. ORNL and Idaho National Laboratory are collaborating to refine the data on costs and capacities for modeling biomass supply systems using models, such as IBSAL. Those values are critical to generate meaningful data from the model.

Initial tests show that the model is sensitive to transportation costs in a region, echoing earlier statements on the importance of transportation in the overall supply chain. For instance, the six refineries displayed in Fig. 13 are replaced by two large facilities when transportation costs are decreased. The goal is to provide insight into the cost tradeoffs that affect the overall configuration of the biofuel infrastructure in a region, not to site facilities or route biomass. The model creates an "optimal" configuration based on the objectives and constraints and this can serve as an upper bound on the "best" possible outcome.

Conclusions and Research Recommendations

The review of biomass supply chains and related models and tools available for analysis and design revealed several challenges that hinder the comprehensive understanding and implementation of future applications. This paper has concentrated on some of the most prevalent challenges, including availability and quality of data to analyze the various components of the supply chain, lack of a common framework for sustainability indicators, and deficiency in integrated analysis when developing the supply chains and individual components. Additional challenges exist for large-scale implementation of such systems, such as lack of national or international policies and standardization, understanding the effect of international energy markets on sustainable bioenergy production, and shortcomings of current cellulosic conversion processes.

Evaluating the sustainability of a supply chain is a complex multi-dimensional challenge, making the supply chain components dependent on each other. For example, energy consumption, GHG emissions, and overall environmental impacts should be evaluated in unison with

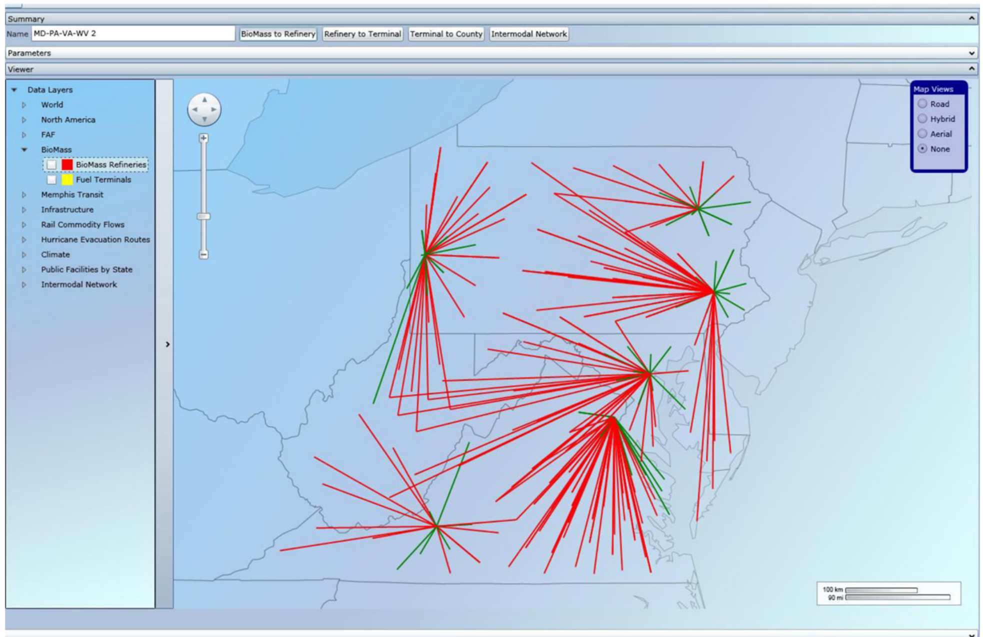

Fig. 13 BILT output displaying the origin and destination of biomass movements from counties to six locations selected as refineries (*red* movements are by truck; *green* are by rail). Source: Authors (Color figure online)

logistics costs, as they vary greatly according to transport and logistical decisions made. The complexity, together with identified challenges, are reflected in the shortcomings of current biomass supply chain models, whether they are comprehensive or targeting a single component of the supply chain. These models require significant amount of data, but in many cases, the modeled analysis has not been field tested at a large enough scale to collect performance data, and collection of such data is costly and time-consuming. Without a common framework and a set of environmental, economic, and social sustainability metrics and indicators to compare across locations, technologies, and practices, it is also difficult to analyze and monitor potential and actual implementations across all the dimensions. The need for integration is demonstrated by the BILT model that currently develops the "optimal" configuration for facilities, transportation, and distribution based on the assumption that everything will be built at once, instead of more realistic scenario of construction in several phases. Similarly, the integrated landscape management cannot be implemented without establishment of the advanced supply feedstock near the point of production.

The recommendations for future research address the challenges and complexities outlined above. First, a common framework should be established that would allow comparison of potential implementations, or the impact of actual implementations. The framework suggested by McBride et al. (2011) and Dale et al. (2013) could function as the foundation for further development. The framework would also assist in developing a common set of sustainability indicators and metrics, which would then function as the basis for a more robust collection and testing of data in the international setting.

Second, an improved integration of the supply chain and related analysis is vital to future current models and systems. A more realistic representation of the biofuel supply chain requires expanding the analysis of different logistics frameworks and incorporating the temporal sequencing of infrastructure construction.

Third, from a transportation logistics perspective, the use of new technologies, such as tracking vehicles with GPS/GPRS devices to indicate the nearest trucks available, should be expanded to better understand the vehicle movements and minimize needed resources for transportation. Similarly, routes should be optimized using algorithms to indicate the most economic path considering tolls, road conditions, elevations, time, and distance. From a multi-modal perspective, the cost and environmental benefits over trucking should be evaluated together with the advanced supply chains that can better take advantage of alternative transportation options, and further work should be done in improving the equipment efficiencies.

Fourth, from an implementation perspective, creating a robust biomass trading market that can couple diverse and distributed crops to energy producers requires establishing biomass commodity feedstocks which are stable, dense, flowable, and predictable in their material specifications. Advanced supply systems are essential to implement more sustainable biomass production schemes and preprocessing steps which convert raw biomass into a larger scale tradable commodity feedstock to be moved to market. Implementation will be especially critical for new bioenergy feedstocks, but present biofuels may also see improvements in the value chain with benefits for the food, feed, and fiber industries.

Finally, the sustainability of the biofuel industry depends on its capability to develop a supply chain that is economically competitive. Hence, the economics of the international energy markets should be incorporated in the analysis, as well as economic models of the integrated supply chain and its individual components. Without component level models, it will be difficult to demonstrate the benefits of the supply chain to the individual players, or develop chains that secure incentives for all participating bodies. One alternative toward better understanding of the integrated systems would be to study examples that already exist, such as biomass use and logistics in Finland, a country with severe climate during winter and a large use of biomass for heat and electricity. Knowledge transfer from such practices could prove monumental in the development of the biofuels industry for the Pan American region.

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