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Techno-economic analysis and life cycle assessment of the corn stover biomass feedstock supply chain system for a Midwest-based first-generation cellulosic biorefinery

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Techno-economic analysis and life cycle assessment of the corn stover biomass feedstock supply chain system for a Midwest-based first-generation cellulosic biorefinery

by

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DEDICATION

To My Dad

Shital Prasad Shah (1952-2008)

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ABSTRACT

Corn stover is the primary feedstock choice for most of the first-generation cellulosic biorefineries in the Midwest, and their rated capacities are in between 76 and 114 million liters per year (MLPY) (i.e., 20 and 30 million gallons per year (MGPY)). For the uninterrupted operation of these plants, a year-round supply of corn stover needs to be secured, which will require a robust, efficient, cost-effective and environmentally-balanced feedstock supply chain. However, there is limited techno-economic and environmental know-how in this area. Thus, the main objective of this dissertation is to stochastically analyze the technoeconomics, life-cycle energy use, and greenhouse gas emissions (GHGE) of the corn stover biomass feedstock supply chain having high likelihood of industrial implementation by the first-generation Midwest-based 114 MLPY (30 MGPY) cellulosic biorefineries using production-scale field data collected in Iowa. Different components of this supply chain include corn stover harvesting, collection and stacking at the field-edge, handling and transportation of bales from the field-edge to the distributed centralized facilities for storage, and then to the biorefinery plant, and finally the audit of nutrients removed with stover from the field. A Midwest-based 114 MLPY cellulosic biorefinery, on an average, requires around 374 thousand std. Mg (413 thousand std. ton) of corn stover feedstock each year, and the execution of different supply chain activities to deliver this quantity of stover to the plant, on an average, requires around 250 thousand hours equivalent of labor and 4.3 million L (1.2

million gal) of diesel fuel. Average cost, energy use, and GHGE for biorefinery gate delivered stover are estimated to be 121.9 \$-std. Mg^{-1} (110.6 \$-std. ton^{-1}), 1502 MJ std. Mg^{-1} (1.3 million BTU std. ton^{-1}), and 95.2 kg-CO_2e std. Mg^{-1} (190.4 lb-CO_2e std. ton^{-1}), respectively. Furthermore, bale density and length, harvest rate, baler field efficiency and fuel consumption, dry matter loss, nitrogen removed with stover harvest, and harvest window are the top five parameters influencing the overall cost, energy use, and GHGE of the supply chain. In addition to these results, this dissertation discusses some potential strategies to reduce the supply chain costs, energy use, and GHGE.

CHAPTER I

INTRODUCTION

1.1. Background

Energy security and global climate concerns are the primary motivations for the partial shift toward biobased energy sources. In the United States, biofuels production and consumption have been long encouraged as evident by different policies enacted at the state and federal levels. For instance, the US Energy Tax Act of 1978 (ETA) provided 1.06 cents L^{-1} (i.e., 4 cents gal^{-1}) subsidy to the blend of gasoline with at least 10% non-fossil fuel based ethanol by volume (Solomon et al., 2007). This was equivalent to 10.57 cents subsidy for a liter (i.e., 40 cents subsidy for a gallon) of ethanol. The phase-out of leaded gasoline by U.S. Environmental Protection Agency (EPA) in the 1980s led to increased interest in using ethanol as an octane booster and volume enhancer; however, methyl tertiary-butyl ether (MTBE) dominated the most oxygenated gasoline markets over the use of ethanol (Solomon et al., 2007). Beginning 2004, there were increased restrictions on the use of MTBE as fuel additive mainly due to its causing cancerous groundwater contamination. This led to the rapid growth in ethanol industry as an alternative fuel additive for gasoline (Solomon et al., 2007; Sorda et al., 2010). The biofuels production got further boost when the U.S. Congress passed Energy Independence and Security Act (EISA) of 2007. Revised renewable fuel standard (RFS2) authorized under EISA mandates the production of 136.3 billion L (36 billion gal) of renewable biofuels, including 60.6 billion L (16 billion gal) of cellulosic biofuels, by 2022.

Achievement of the national cellulosic biofuels production target set by RFS2 will require around 181 million dry Mg (200 million dry ton) of cellulosic feedstock delivered to the biorefineries annually (BRDI, 2008) through an economically and environmentally viable feedstock supply chain. The updated billion ton study (BT2) (DOE, 2011), a comprehensive study carried out by the U.S. Department of Energy, provides estimates on the current and potential agronomically and ecologically sustainable quantity of cellulosic biomass feedstock availability in the U.S. under baseline (assuming a continuation of the USDA 10-year forecasts for the major food and forage crops, and extending up to 2030) and high yield scenarios (based on the expert opinions on the development of industry-based, high-yield alternatives to the baseline assumptions) for the years 2012 through 2030. BT2 (DOE, 2011) estimated the potential availability of agricultural residues, energy crops and forest residues for these years at different farmgate or forest roadside prices. At 66 \$-dry Mg^{-1} (60 \$-dry ton^{-1}) or less farmgate or forest roadside price of feedstock, their estimated total cellulosic biomass availability under the baseline and high-yield scenarios are around 0.81 and 1.13 billion dry Mg (i.e., 0.90 and 1.25 billion dry ton), respectively, in 2022, and around 0.99 and 1.36 billion dry Mg (i.e., 1.10 and 1.50 billion dry ton), respectively, in 2030 (Figure 1.1). This feedstock availability far outweighs the feedstock requirements for meeting cellulosic biofuels production target set by RFS2.

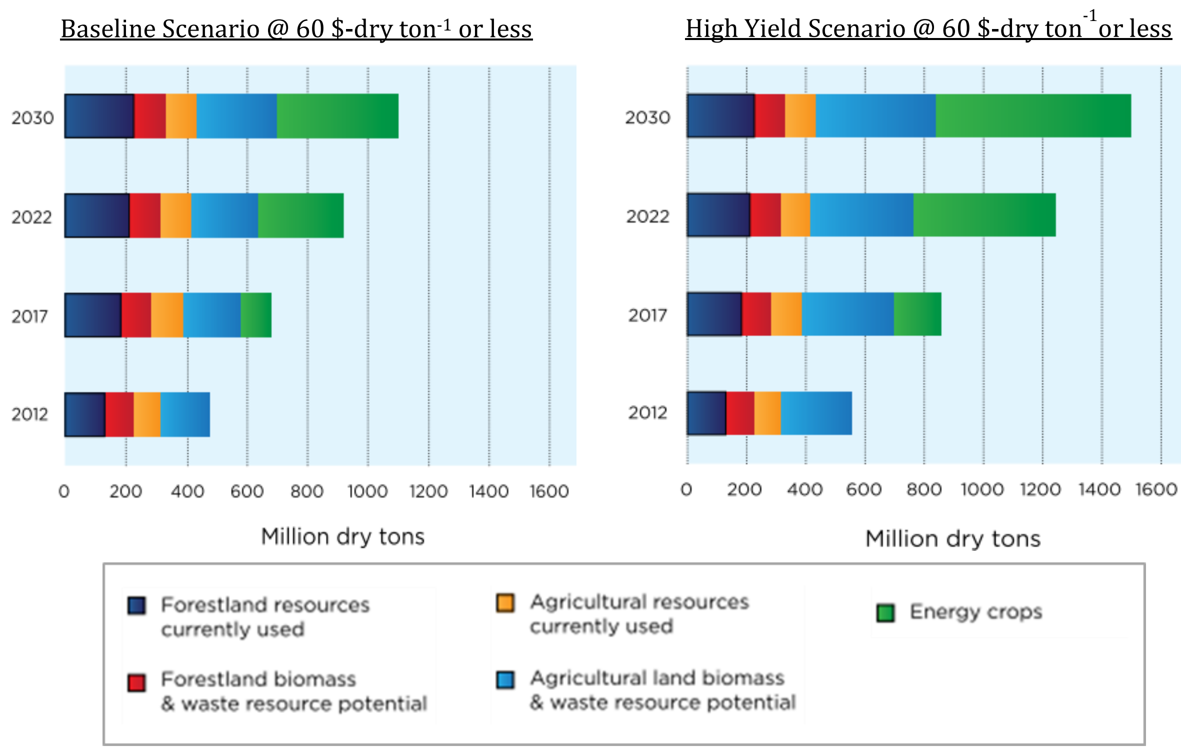

Figure 1.1: Summary of estimates on currently used and potential biomass resources at 66 \$-dry Mg^{-1} (60 \$-dry ton^{-1}) or less price of biomass to farmgate or roadside, as made by billion ton update study (DOE, 2011) under baseline and high yield scenarios (This figure is adopted from BT2 (DOE, 2011), and the values presented are in U.S. customary units)
(Note: *This figure is adopted from BT2 (DOE, 2011), and any future citations for this figure should be directed to the original work and not this work.*)

BT2 (DOE, 2011) estimates indicate that under both the baseline and high-yield scenarios, agricultural residues (current and potentially available) constitute more than half the total U.S. feedstock potential in 2012, and around one-thirds in 2030. BT2 (DOE, 2011) results also indicate that the energy crops will have increasing share in overall feedstock from none in 2012 to around 40% in 2030. Figure 1.2 provides the distribution and shares of potentially available biomass in different states in 2030, and illustrates that almost all the agricultural residues will come from the Midwestern states. Further analysis of BT2 (DOE, 2011) estimates indicate that at the feedstock farmgate price of 66 \$-dry Mg^{-1} (60 \$-dry ton^{-1}) or less, the corn stover share of the overall potentially available agricultural residues will be more than 50% in baseline scenario and more than 65% in high-yield scenario throughout the years 2012 to 2030. Quantitatively, BT2 (DOE, 2011) estimates for potential annual availability of agronomically and ecologically sustainable corn stover feedstock at farmgate price of 66 \$-dry Mg^{-1} (60 \$-dry ton^{-1}) or less and through the years 2012 to 2030 are in the ranges 77-127 million dry Mg (i.e., 85-140 million dry ton) in baseline scenario and 138-246 million dry Mg (i.e., 153-271 million dry ton) in high-yield scenario. Furthermore, BT2 (DOE, 2011) has cited corn as-"*the most important residue-producing crop with the greatest potential for yield improvements and management of residue production.*" These comprehensive analyses indicate that corn stover will be the primary feedstock for cellulosic biorefineries in the Midwest. The likelihood of corn stover to be the principal feedstock source in this region is further evident with it being the choice of the two first-generation commercial cellulosic biorefineries in Iowa (DuPont, 2013; POET-DSM, 2013). Based on these arguments, and considering the fact that this study has been conducted in Iowa-a primary corn growing Midwestern state (USDA, 2013), discussions hereafter will be focused on corn stover feedstock (Please note: any use of the words-"feedstock" or "biomass" or "stover" hereafter should be considered as "corn stover biomass feedstock" unless otherwise mentioned).

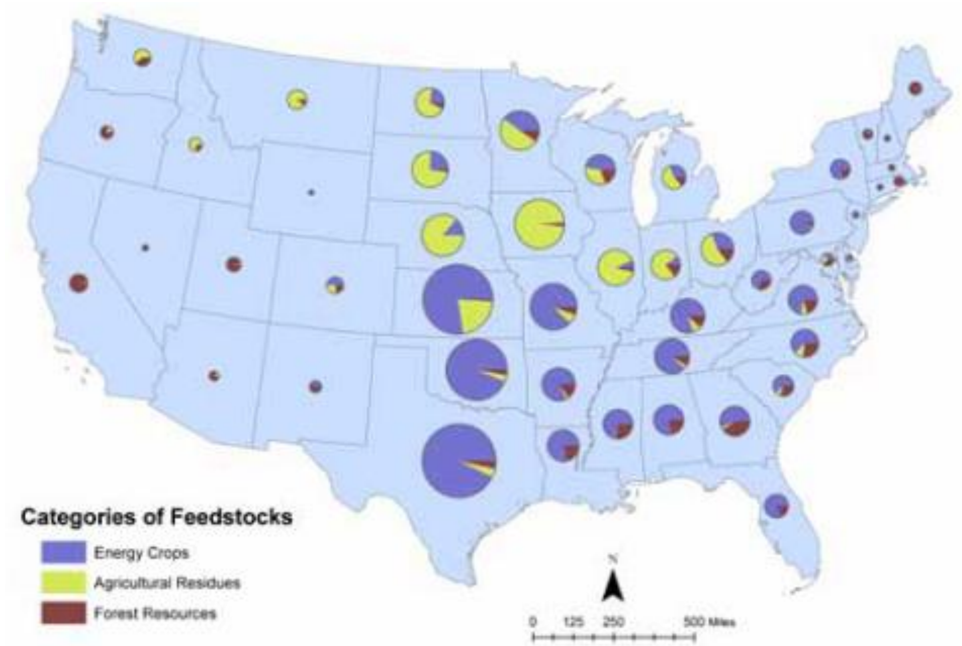

Figure 1.2: State-level distribution and relative shares of all potentially available cellulosic biomass (i.e., agricultural residues, forest residues and energy crops) at 66 \$-dry Mg^{-1} (60 \$-dry ton^{-1}) or less farmgate or roadside price under baseline scenario in 2030
(Note: *This figure is adopted from BT2 (DOE, 2011), and any future citations for this figure should be directed to the original work and not this work.*)

With the prospects of harvesting corn stover for cellulosic biofuels production, there have been growing concerns and efforts to quantify its impacts on soil organic matter pool, wind and water induced soil erosion, and nutrients removal (Blanco-Canqui and Lal, 2007; 2009; Cruse and Herndl, 2009; Hoskinson et al., 2007; Johnson et al., 2010; Karlen et al., 2011; Lindstrom, 1986; Mann et al., 2002; Nelson, 2002; Wilhelm et al., 2007; Wilts et al., 2004). BT2 (DOE, 2011) estimates for agricultural residues availability in the U.S. are constrained by the tolerable soil loss limit (as recommended by the USDA's Natural Resource

Conservation Service (NRCS)), and the amount of residue removal without compromising the long-term loss of soil organic matter (as estimated by Revised Universal Soil Loss Equation (RUSLE2) and the Wind Erosion Prediction System (WEPS)). Soil erosion removes SOM and nutrients resulting in direct loss of soil productivity; however, this is inevitable as some degree of soil erosion occurs due to rain and wind. Furthermore, suspended solids and nutrients (nitrogen, phosphorus and potassium) washed away by rain or wind erosion results in surface and ground water quality degradation. In addition to the loss in soil productivity and water quality degradation caused by soil erosion, removal of SOM adversely impacts soil productivity, nutrient cycling, filtering and buffering of potential pollutants, water storage and resistance to compaction and erosion (DOE, 2011).

Previous studies have suggested the replenishment of nutrients, mainly nitrogen (N), phosphorus (in terms of P_2O_5) and potassium (in terms of K_2O), removed due to stover harvest from the field. These nutrients are essential for plant growth and need to be replenished during subsequent year farming. It is unclear whether a partial stover removal will reduce the amount of organic nitrogen over the long-term, thereby, needing farmers to replenish N through fertilization. Coulter and Nafziger (2008) have found compensating effects of stover removal on nitrogen fertilizer needs. Although harvesting of stover removes a small amount of N from the field, it reduces the amount of N immobilized in the soil the following year (Johnson et al., 2007). In continuous corn cropping system, removing a portion of the corn stover helps increase N mineralization (Halvorson et al., 2001) and can reduce the overall N fertilizer requirement (Coulter and Nafziger, 2008). On the other hand, some studies (Johnson et al., 2010, Edwards, 2011) have suggested that the removal of nutrient through corn stover harvesting carries a significant replacement cost in addition to adverse effects of stover harvesting on soil organic carbon loss (Wilhelm et al., 2004, Blanco-Canqui and Lal, 2009), soil erosion (Mann et al., 2002), and runoff nutrient loss (Wienhold and Gilley, 2010).

With consideration of the potential adverse effects caused by stover removal from the field for biofuels purposes, several researchers have suggested different practices for sustainable stover removal. For instance, Johnson et al. (2007) have used linear regression to provide estimates of corn stover that could be harvested without reducing soil organic carbon as a function of corn yield under different cropping and tillage practices (Figure 1.3). Based on their recommendations, the highest quantity of corn stover can be removed from the field in continuous corn with reduced tillage. Blanco-Canqui and Lal (2007 and 2009) have suggested that only about 25% or less stover could be sustainably removed for biofuels feedstocks from sloping and erosion-prone soils. Johnson et al. (2010) suggests that compared to whole stover removal, collecting cobs or above-ear stover fraction may provide a higher quality feedstock while removing fewer nutrient. Karlen et al. (2011) found that the average continuous corn yields were 21% lower than those of rotated corns with no significant differences due to stover harvest. Furthermore, Hoskinson et al. (2007) have recommended harvesting stover (including the cobs) at a height of approximately 40 cm due to observed advantages as faster harvest speed and producing higher quality ethanol feedstock.

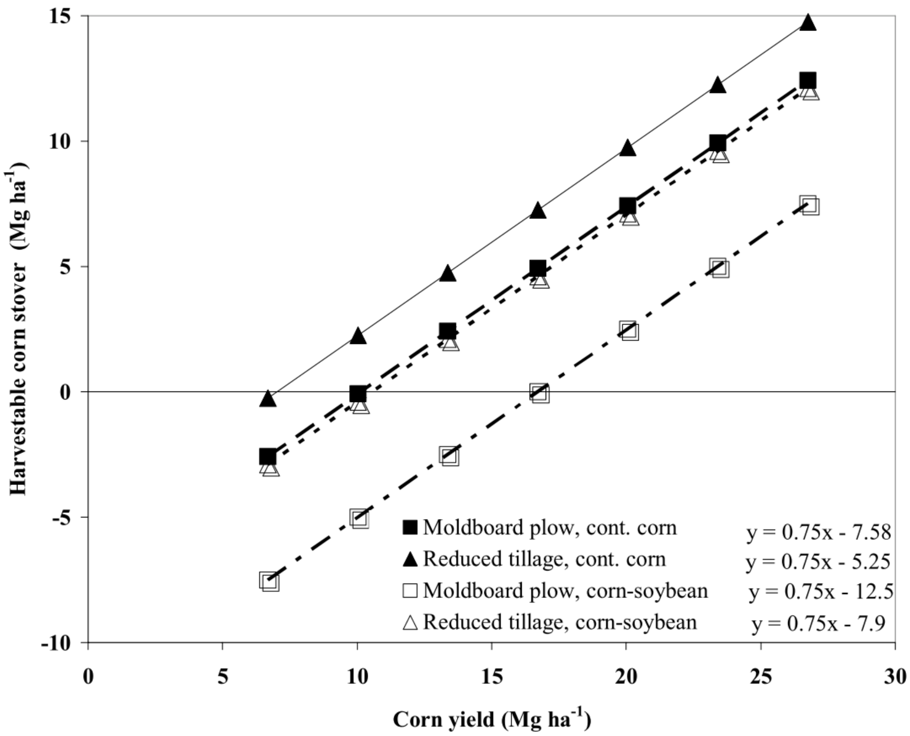

Figure 1.3: Allowable quantities of corn stover that could be harvested without reducing soil organic carbon as a function of corn yield in different cropping and tillage practices.
(Note: *This figure is adopted from Johnson et al. (2007), and any future citations for this figure should be directed to the original work and not this work.*)

Based on the discussions so far, it is evident that the United States has enough potential to supply the required quantities of biomass feedstock to meet EISA biofuels production mandates in agronomically and economically sustainable ways. Furthermore, corn stover will share a significant fraction of the overall feedstock supply for producing cellulosic biofuels, and, thus will play a pivotal role in the overall success of the biobased economy. However, collecting this huge quantity of cellulosic feedstock from the field/source and delivering to the biorefinery plant will face significant techno-economic and environmental challenges due to limited know-how in this area. This chapter depicts five potential alternative corn stover biomass feedstock supply chains capable of handling and delivering corn stover feedstock to the biorefinery in the present (immature, commercially small-scale operation) and future (mature, commercially large-scale operation) scenarios. The next two chapters of this dissertation analyze the current techno-economics, and life-cycle energy use and greenhouse gas emissions for a corn stover feedstock supply chain identified in this chapter to have the highest likelihood of adaptation by the Midwest-based first-generation cellulosic biorefineries.

Feedstock supply chains for cellulosic biorefineries involve different activities associated with collecting cellulosic biomass from its source to preparing it for the final conversion to biofuels meeting biorefinery quality, cost and environmental requirements. Moisture and ash contents are the two major quality metrics of feedstock for the cellulosic biorefineries. Moisture content is the measure of the water content (internal and external) in the biomass feedstock, and ash content is the measure of non-lignocellulosic impurities in the biomass. It can either be the internal structural ash inherent to biomass feedstock or the nonstructural ash which is soil contamination entrained in the biomass bale predominantly during harvesting (Darr and Shah, 2012). POET-DSM (2013) has set the moisture and ash content levels of less than 35 and 15% for no dock price. For feedstock moisture levels of 35-50%, they have set the dock price of 5.5 \$-bone dry Mg $(BDM)^{-1}$ (5 \$-bone dry ton $(BDT)^{-1}$), and for ash levels of 15-25%, their dock price is 11 \$-BDM^{-1} (10 \$-BDT^{-1}). Additionally, they have decided to reject any feedstock above 50% moisture and 25% ash contents. Apart from moisture and ash, POET-DSM (2013) has not mentioned anything about the feedstock quality requirements for incoming feedstock. According to Muth (2013), biochemical conversion requires the feedstock quality specification of more than 59% sugars, and less than 20% moisture and 7% ash; and thermochemical conversion requires less than 10% moisture and 1% ash contents. Depending upon these information and considering the fact that this study is carried out in Iowa where both the first-generation cellulosic biorefineries to be operational within the next two years employ biochemical conversion method, this dissertation sets 0% moisture and 8% ash contents as 'standard' biomass quality metrics; and has normalized all the results presented in Chapters 2 and 3 to these standard conditions (i.e., 0% moisture and 8% ash contents).

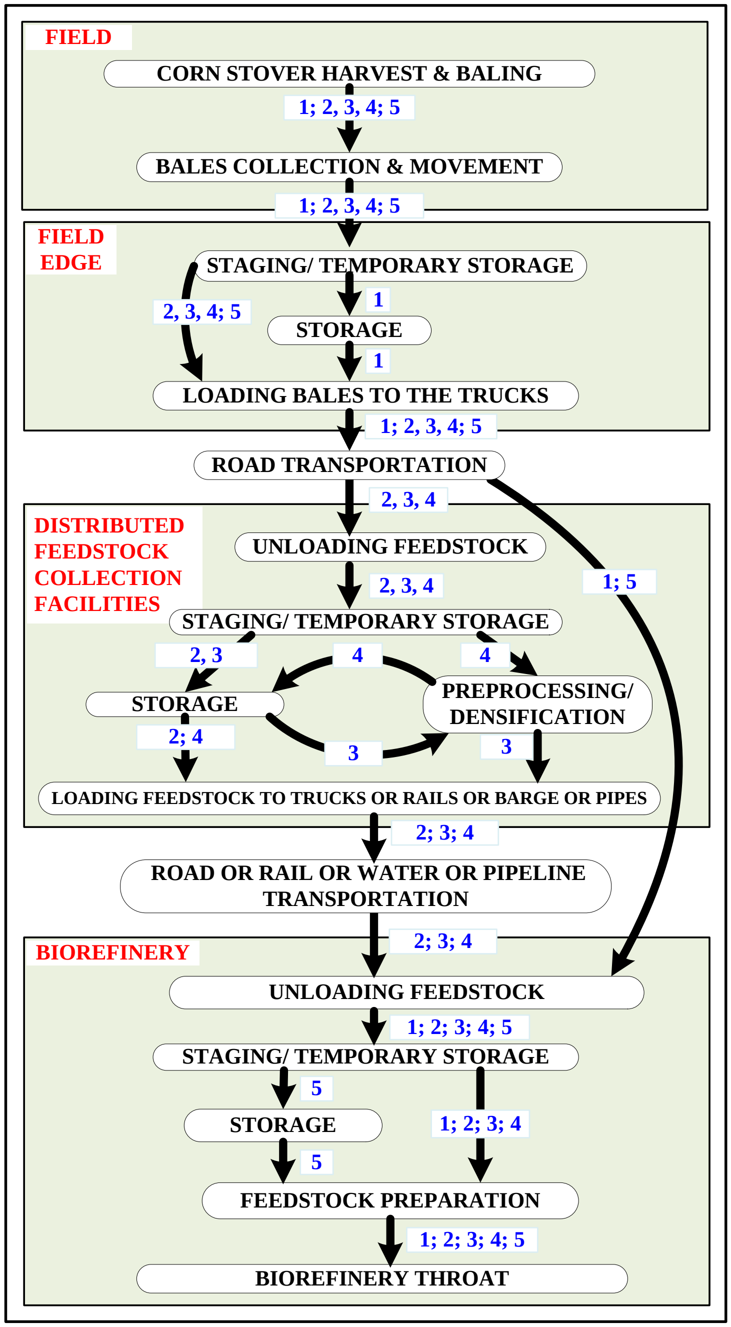

Figure 1.4: Five alternative corn stover biomass feedstock supply chains having potentials to be implemented by the cellulosic biorefineries in the present (immature, commercially small-scale operation) and future (mature, commercially large-scale operation) scenarios.

(Note: *Different lines connected with same numbers represent unique corn stover feedstock supply chain configuration*)

Box 1.1: Five alternative corn stover biomass feedstock supply chains having potentials to be implemented by the cellulosic biorefineries in the present (immature, commercially small-scale operation) and future (mature, commercially large-scale operation) scenarios

Alternative Corn Stover Supply Chain (SC) Options:

SC 1: Storage at the field-edge followed by truck transportation of bales to the biorefinery gate.

SC 2: Truck transportation of bales from the field-edge to the distributed feedstock collection facilities (DFCF), storage at DFCF followed by truck transportation of bales to the biorefinery gate.

SC 3: Truck transportation of bales from the field-edge to DFCF, storage followed by feedstock preprocessing (upgrading and/or densification) at DFCF, truck or rail or barge or pipeline transportation of preprocessed feedstock to the biorefinery gate.

SC 4: Truck transportation of bales from the field-edge to DFCF, feedstock preprocessing (upgrading and/or densification) followed by storage at DFCF, truck or rail or barge or pipeline transportation of preprocessed feedstock to the biorefinery gate.

SC 5: Truck transportation of bales from the field-edge to the biorefinery gate followed by storage at the biorefinery site.

Five alternative corn stover biomass feedstock supply chains having potentials to be implemented by the cellulosic biorefineries in the present (immature, commercially small-scale operation) and future (mature, commercially large-scale operation) scenarios are depicted in Figure 1.4. Brief distinctions of these supply chains are made in Box 1. These alternative corn stover biomass feedstock supply chains are formed of the unique combinations of corn stover harvesting in bale format, in-field bale collection and movement to the field-edge, handling and transportation of stover from the field-edge or distributed feedstock collection facilities (DFCF) to the DFCF or the biorefinery plant, feedstock preprocessing for densifying or upgrading of feedstock at DFCF, storage, and final feedstock preparation in the form ready for conversion to biofuels. Different supply chains are distinguished mainly based on the feedstock storage location (i.e., field-edge, DFCF or biorefinery plant), inclusion of preprocessing at DFCF, and the form of feedstock transportation to the biorefinery. Hereafter, different supply chains discussed in this chapter will be referred to as “SC” followed by the numbers 1-5, and will signify the ones illustrated in Figure 1.4 or Box 1.1.

In the current context, corn stover biomass, after grain harvest, will be collected from the fields in large rectangular bale format with cross section of 1.22 m (4 ft) wide and 0.91 m (3 ft) high, and length of 2.4 m (8 ft) (Darr and Shah, 2012; Sokhansanj and Hess, 2009; Sokhansanj et al., 2010). Alternately, collection of stover in round bale, loaf and bulk formats are also possible, however, large rectangular bale format has been envisioned as the primary choice in the near term. Details of the other methods of stover collection are explained in detail by Sokhansanj and Hess (2009). Conventionally, corn stover bale is harvested in multiple passes through the field, wherein grain harvest is followed by windrowing (shredding or raking), baling and in-field bale collection and movement to the field edge. Richey et al. (1982) have provided further details on multi-pass harvesting system. The principal disadvantage of multi-pass harvesting is the soil contamination of biomass especially during the windrowing operation. In addition to this, other problems of multi-pass harvesting, especially in the Midwest, include poor drying condition due to short day length and low ambient air temperatures, short time period between grain harvest and snow cover, frequent weather delays, low harvest efficiency and high cost (Shinners et al., 2007a, 2007b). A way to overcome some of the shortcomings of multi-pass harvesting is to use single-pass harvesting, which collects both the grain and stover in the same pass of machinery through the field, thus, reducing soil contamination by picking up stover without allowing it to drop on the field, and potentially minimizing the soil compaction due to less passes of machineries through the field. A major disadvantage of single-pass harvesting system is the loss of opportunity to field-dry the stover after harvest, which can increase biological degradation of biomass during storage as well as incur additional cost for drying to meet moisture requirements for different biofuels conversion processes. In recent years, several researchers, including Shinners et al. (2007b), Shinners et al. (2009) and Webster et al. (2010), have investigated the performances of single-pass harvesting system for corn stover collection in bale format. A pictorial delineation of multi- and single-pass corn stover bale harvesting methods has been presented in figure 1.5. In long run, both of these corn stover harvesting systems will be the part of the overall feedstock supply chain; however, in near term established multi-pass harvesting system will be the predominant choice of the supply chain operators.

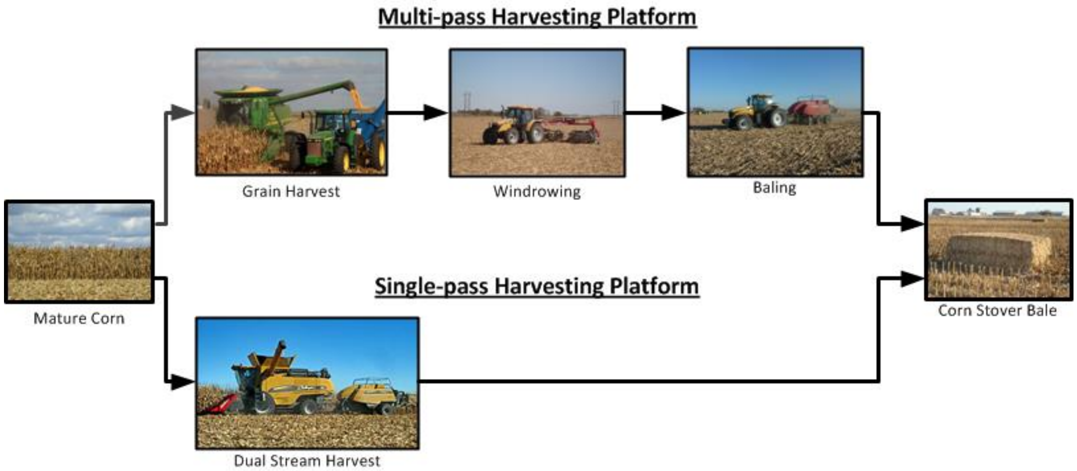

Figure 1.5: Single- and multi-pass corn stover bale harvesting pathways

Figure 1.6: Corn stover bales spread in the production biomass field following harvest
(Note: *modified from Darr and Shah (2012)*)

Following harvest, corn stover bales are spread all across the field (Figure 1.6), thus, needs to be collected and stacked to the concentrated location, usually field-edge, for further handling and transfer to the other locations. This is generally accomplished with the use of multiple bale collection wagons having capacities of collecting 12 bales in their single trip through the field in an on-the-go basis. Externally-powered and self-propelled multi-bale collection wagons are shown in Figure 1.7.

Figure 1.7: In-field multi-bale collection wagon in action (Left picture shows the externally-powered pull-type multi-bale collection wagon; and right picture shows the self-propelled Stinger multi-bale collection wagon)
(Note: *left picture modified from Darr and Shah (2012)*)

The stover bales, stacked at the field-edge, can either be stored at the same location (applicable to SC 1, as depicted in Figure 1.4) or loaded to the trucks for delivery to DFCF (applicable to SCs 2-4, as depicted in Figure 1.4) or to the biorefinery plant (applicable to SC 5, as depicted in Figure 1.4). The best option for field-edge bale storage, as applicable to the supply chain 1 (Figure 1.4), is with tarp cover (Figure 1.8). The alternative bale storage options (Figure 1.8), including tube-wrapped and permanent structure storage, are not feasible for field-edge storage. Permanent structure storage at the field-edge is limited by only seasonal availability of lands for storage activities at that location. Tube-wrapper can wrap only 3-bales high stack, but the multi-bale collection wagons, discussed earlier, stack bales 6-units high, thus, requiring additional equipment specifically for storage purposes in the peak season when most of the resources are utilized by harvesting operations. Further details on different options for industrial-scale bales storage are discussed by Darr and Shah (2012). Bales at the field-edge (before or after storage, as applicable to different supply chains) are loaded on the semi-trucks with flat-bale trailers using squeeze loader (Figure 1.9), and delivered to their designated destination. Alternately telehandlers can be used to load bales onto the trucks, however, squeeze loaders are advantageous due to their ability to handle 6 bales in a single cycle compared to 3 for telehandlers, as well as, unlike telehandlers, squeeze loaders do not physically pierce bales, thus, maintaining better bale integrity. Truck with 2.4 m (8 ft) wide and 14.6 m (48 ft) long flatbed trailer can transport 36 bales in a single trip, and is the single feasible option for bale transport from the field-edge.

Figure 1.8: Industrial-scale biomass storage methods (top-left: tarped storage; top-right: permanent structure storage within hoop barn; bottom-both: tube-wrapped storage)
(Note: *top-right, bottom-left and bottom-right pictures modified from Darr and Shah (2012)*)

Corn stover bales after being received at DFCF can be stored in one of the previously explained ways (Figure 1.8) followed by truck transportation of stored bales to the biorefinery (applicable to SC 2, as depicted in Figure 1.4) or preprocessing them for densification or quality upgrading before transportation to the biorefinery (applicable to SC 3, as depicted in Figure 1.4). The next likely scenario can be preprocessing corn stover bales received at DFCF for densification or quality upgrading before storage and transportation to the biorefinery (applicable to SC 4, as depicted in Figure 1.4). Decision to include preprocessing earlier in the supply chain will mainly be governed by the size of the biorefinery plant. With the increase in the sizes of biorefinery plants, their feedstock demand will increase which will further increase the collection area and the travel distance between the field-edge or DFCFs and the biorefinery plant. In such scenario, truck transportation of corn stover bales will be cost prohibitive, and any effort to increase the feedstock density will contribute to direct economic gain by reducing transportation cost primarily by increasing the payload. Feedstock can be densified in different ways, including briquetting, pelletization and cubing. When compared to the bale format, briquetting, pelletization and cubing can increase the bulk density of feedstock by around 2 to 4 times (based on bale density of 150 kg m^{-3}, and the data from Sokhansanj and Hess (2009)). Likewise, corn stover bales can be upgraded to higher value products through methods, including torrefaction and pyrolysis. Compared to bale format, torrefaction increases the energy density and brittleness, improves hydrophobicity and microbial degradation resistance of feedstock (Medic et al., 2012; Shah et al., 2012). These improvements in feedstock property has a direct gain in the overall feedstock supply system by enhancing grindability, attaining uniformity among different feedstock types, and reducing dry matter loss during storage. Pyrolysis converts the stover to liquid form (bio-oil), which can be upgraded to biofuels by gasification and synthesis or hydrotreatment or zeolite cracking or to hydrogen by steam reforming. Bridgwater (2011) provides further details on these bio-oil upgrading processes. Additionally, biochar produced as the co-product of pyrolysis can be applied to the agricultural lands resulting in increased soil organic matter and, thus, soil productivity, as well as aiding in carbon sequestration. As applicable to supply chain 4 (Figure 1.4), densified and torrefied feedstock can be stored at DFCF in storage bins or silos identical to that in the grain industries, whereas bio-oil can be stored in tanks identical to that in the petroleum industries.

Figure 1.9: Loading bales to the truck trailer using squeeze loader (top), and transportation from the field-edge to DFCF or biorefinery plant using truck (bottom)
(Note: *top picture modified from Darr and Shah (2012)*)

Converting stover to liquid form (bio-oil) opens up options for pipeline transportation to the biorefineries; however, there is a need to study the techno-economic and environmental feasibility of this option before commercialization. Additionally, for the supply chains 2-4, depending upon the travel distance between DFCF and biorefinery plant, alternative transportation modes, as rails and barge, can be selected. Sokhansanj and Hess (2009) have shown that the truck transportation is economical than rail transportation up to the travel distance of 110 km; however, before arriving at any conclusion regarding cutoff travel distances for different transportation modes, further detailed techno-economic and environmental assessments are required. Thus, different preprocessing methods can have direct gain in the post-preprocessing transportation activities (applicable to alternative supply chains 3 and 4, as depicted in Figure 1.4); however, investment made for these processes need to be justified which can be done by assessing their costs, resource requirements, environmental emissions and qualities impacts on that of the overall supply chain.

Final step in all five alternative supply chains (Figure 1.4) is to receive feedstock (either directly from the field or stored and/or preprocessed) at the biorefinery plant, and provide temporary storage before preparing for the conversion to biofuels. For supply chain 5 (Figure 1.4), corn stover bales will be stored at the biorefinery plant in one of the ways discussed earlier, and illustrated in Figure 1.8. The final step requires meeting feedstock conversion requirements of the biorefineries which involves size reduction as well as meeting quality requirements. As discussed earlier, moisture and ash are the two major quality metrics for the cellulosic biorefineries. Depending upon the feedstock conversion method of the biorefinery (i.e., thermochemical or biochemical), feedstock needs to be prepared differently. Muth (2013) has suggested the allowable feedstock moisture, ash and particle size of feedstock for thermochemical conversion as 10%, less than 1% and 2-6 mm, respectively, and for biochemical conversion as 20%, 7% and 6-19 mm, respectively. However, all feedstock received at the biorefinery do not meet these specifications necessitating feedstock preparation before feeding into biorefinery throat. Size reduction is usually attained by grinding or milling. Moisture content can be reduced by drying, and ash content by sieving. In addition to these, desirable moisture and ash contents can be attained by blending feedstock with low and high moisture and ash contents.

In the near future, especially within the first few years of the commercial deployment and operation of the first-generation cellulosic biorefineries, supply chains 1, 2 and 5 will be the likely choices of biorefineries for acquiring feedstock, primarily due to their smaller rated biofuels production capacities, i.e., in between 76 and 114 million liter per year (MLPY) (20 and 30 million gallon per year (MGPY)). Supply chain 2 will play the predominant role in feedstock supply business; and, supply chains 1 and 5 will be the smaller part of the mix. Supply chain 1 is limited primarily by the location in that irregular field-edge storage surface lacking proper drainage would cause increased degradation of dry matter, the complexities associated with assessing feedstock stored at the field edge after the weather condition worsens in winter in the Midwest, and the availability of land for storage only between harvest and the new plantation season. Supply chain 5 is limited primarily by the need to transport huge quantity of biomass from the field edge to the biorefinery plant within a shorter working duration of less than two months to combat the potential logistical complexities arising in the winter months due to worsening weather conditions. Nonetheless both of these supply chains will contribute to some extent toward delivering feedstock to the biorefinery, but supply chain 2 will have the major share. Supply chain 2 is advantageous in that feedstock can be moved to the scattered DFCFs covering smaller zones during the busy and short working window of less than two months, where these can be stored and finally delivered to the biorefinery plant as required. In the long run, this supply chain will start to be cost prohibitive as the biorefineries will increase their biofuels production capacities, made possible by the technological advancement and maturity, requiring higher quantities of feedstock. In such scenario, biorefineries will incline toward feedstock supply chains 3 and 4 which incorporates preprocessing step early in the supply chain at DFCFs to increase density or upgrade feedstock (See earlier discussion). This will have direct gain in overall economics of the biofuels, mainly by reducing the cost to transport feedstock from DFCFs to the biorefinery. However, thorough techno-economic analysis and life cycle assessment need to be performed to gauge the impacts of incorporating preprocessing step early in the supply chain on the overall supply chain cost and resource requirements, as well as life cycle energy use and greenhouse gas emissions. In this scenario, the other three supply chains (i.e., SCs 1, 2 and 5) will also be the part of the overall feedstock supply solutions, but with decreased shares.

For overall success of the corn stover based cellulosic biorefineries, there is a need to establish economically and environmentally sustainable feedstock supply chain capable of handling and delivering mammoth quantity of corn stover biomass feedstock to the biorefineries. However, there are limited studies focusing entirely on this component of the overall biofuels production supply chain (selected studies on the techno-economics and life-cycle assessment of corn stover feedstock supply chain are thoroughly discussed in Chapters 2 and 3 of this dissertation and will not be repeated here). Additionally, data sources of most of the previous studies are primarily based on small scale operations, which fail to capture the scale of operation anticipated for supplying feedstock for biorefining purposes. Thus, this dissertation seeks to address both of these concerns (i.e., lack of data from large-scale operations as well as the thorough analysis of the viable feedstock supply chain configuration) for corn stover biomass feedstock supply chain. This dissertation focuses on the supply chain 2 (as depicted in Figure 1.4) as this supply chain provides the most viable near-term solution to the feedstock supply needs of the first-generation cellulosic biorefineries in the Midwest. This supply chain involves harvesting corn stover from the field succeeding grain harvest, in-field bale collection and movement to the field-edge, transportation of field-edge stacked corn stover bales to the distributed feedstock collection facilities followed by storage, and the transportation of stored feedstock to the biorefinery gate. In addition to these operations, this study takes into account the nutrients removed from the field with corn stover collection for biorefinery purpose. The primary reason for selecting this feedstock supply chain for this study is its high likelihood to be opted by the first-generation cellulosic biorefineries in the Midwestern U.S. The main emphasis of this dissertation is on stochastically assessing the current techno-economic and environmental performances of this feedstock supply chain, and identifying some of the key parameters influencing its overall cost and resources requirements, and energy use and greenhouse gas emissions. Additionally, this dissertation identifies the area of potential improvement and provides some of the viable solutions for reducing the overall cost and resources requirements, and minimizing the energy use and greenhouse gas emissions of different supply chain operations. Thorough understanding of these metrics is the key to long-term success of the overall cellulosic biorefineries.

1.2. Objectives of the Dissertation

The main objective of this dissertation is to stochastically assess the current techno-economics, and life-cycle energy use and greenhouse gas emissions of the corn stover biomass feedstock supply chain that has high likelihood of industrial implementation by the Midwest-based first-generation cellulosic biorefineries using production-scale field data collected in Iowa. The main objective of this dissertation has been accomplished through the successful execution of the following two specific objectives:

1. Analyze stochastically the techno-economics of corn stover biomass feedstock supply chain of a Midwest-based first-generation 114 million liter per year (i.e., 30 million gal per year) cellulosic biorefinery using production-scale field data collected in Iowa.
2. Estimate stochastically the life-cycle energy use and greenhouse gas emissions for corn stover biomass feedstock supply chain of a Midwest-based first-generation 114 million liter per year (i.e., 30 million gal per year) cellulosic biorefinery using production-scale field data collected in Iowa.

1.3. Intellectual Merit

This study advances knowledge related to corn stover biomass feedstock supply chain that has high likelihood of industrial implementation by the first-generation of cellulosic biorefineries in the Midwestern United States. The results of this work contribute toward fulfilling the existing knowledge gap in techno-economic and environmental know-how of annually handling huge amount of corn stover feedstock for Midwest-based biorefineries. Industrial-scale field data driven results from this study can aid different industries formulate policies in terms of cost and resources requirements, and environmental budgeting. In addition to this, data-driven suggestions presented in this dissertation can be incorporated to significantly reduce the overall cost, energy and greenhouse gas emissions of the corn stover feedstock supply chain. In a long term, the methodologies of this study can be used to develop the economically and environmentally balanced cellulosic biomass supply chain for sustainably delivering sufficient amount of feedstock to the cellulosic biorefineries required for meeting the national biofuels production target, set by EISA (2007).

1.4. Dissertation Organization

This dissertation is organized in four chapters. The first chapter includes the overall background for conducting this research, wherein U.S. biofuels production policies and mandates are discussed, followed by the discussion on the potential availability of cellulosic feedstock, especially corn stover, and the methods to collect corn stover from the field and delivering to the biorefinery. This chapter presents five alternative corn stover feedstock supply chain configurations having potentials to be implemented by the cellulosic biorefineries in the present (immature, commercially small-scale operation) and future (mature, commercially large-scale operation) scenarios. Among these, the one that provides immediate solution to the present stover supply needs has been identified and chosen as the main subject of this dissertation. In addition to these discussions, Chapter 1 presents the objectives, intellectual merits and organization of this dissertation.

The second chapter of this dissertation addresses the first objective of this work, which is to stochastically analyze the techno-economics of corn stover feedstock supply chain identified in the first chapter using production-scale field data collected in Iowa. This chapter stochastically analyzes the resources (equipment, labor, fuel and consumables) requirements and costs of the corn stover feedstock supply chain and its components. Additionally, this chapter identifies and ranks different supply chain parameters based on their relative influences on the overall resources and costs requirements as well as discusses some of the achievable strategies to reduce the overall supply chain cost. This chapter has been drafted as a stand-alone manuscript to be submitted for peer-review and publication to an international journal. This chapter is accompanied with the supporting materials.

Third chapter of this dissertation addresses the second objective of this work, which is to stochastically estimate the life-cycle energy use and greenhouse gas emissions of the same corn stover feedstock supply chain identified in the first chapter and considered for techno-economic analysis in the second chapter using production-scale field data collected in Iowa. The system boundary has been held constant for both the techno-economic analysis (Chapter 2) and life-cycle assessment (Chapter 3) works. Chapter 3 of this dissertation ranks different supply chain parameters based on their influence on the overall life-cycle energy use and greenhouse gas emissions for the supply chain, as well as discusses some of the achievable strategies to decrease the overall energy use and greenhouse gas emissions. This chapter has been drafted as a stand-alone manuscript to be submitted for peer-review and publication to an international journal. This chapter is accompanied with the supporting materials.

The fourth and the last chapter of this dissertation summarizes the main highlights of this dissertation research. Additionally, this chapter extends some of the suggestions for future research in this area in light of this undertaking.

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CHAPTER II

TECHNO-ECONOMIC ANALYSIS OF THE CORN STOVER BIOMASS FEEDSTOCK SUPPLY CHAIN SYSTEM FOR A MIDWEST-BASED FIRST-GENERATION CELLULOSIC BIOREFINERY USING MULTIPLE YEAR PRODUCTION-SCALE FIELD DATA COLLECTED IN IOWA

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2.1 Abstract

The primary feedstock choice for most of the first-generation cellulosic biorefineries planning commercial operation in the Midwest is corn stover and their rated capacities are in between 76 and 114 million liter per year (MLPY) (i.e., 20 and 30 million gallon per year (MGPY)). Thus, for uninterrupted operation of these plants, a year-round supply of corn stover needs to be secured, which will require a robust, efficient and cost-effective feedstock supply chain. The main objective of this work is to stochastically analyze the techno-economics of corn stover biomass feedstock supply chain for a 114 MLPY (30 MGPY) cellulosic biorefinery in the Midwest using production-scale experimental field data collected in Iowa. This study analyzes the resources requirements (equipment, labor, fuel and consumables) and costs of different components of the supply chain including harvesting (windrowing and baling), in-field bales collection and stacking at the field-edge, handling and transportation of bales from the field-edge to the distributed central storage facilities and, then, to the biorefinery plant, storage, and finally the audit of nutrients removed during stover collection from the field. Additionally, this study identifies and ranks different supply chain parameters based on their relative influences on the overall resources and costs requirements as well as discusses some of the achievable strategies to reduce the overall supply chain cost. A Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery plant, on an average, requires around 0.95 million corn stover bales supply, 250 thousand hours equivalent of labor and 4.3 million L (1.2 million gal) of diesel fuel each year. Average cost of biorefinery gate delivered corn stover biomass feedstock is estimated to be 121.9 \$-std. Mg^{-1} (110.6 \$-std. ton^{-1}). The most likely overall supply chain cost is identified to be the most sensitive to bale density followed by harvest rate, bale length, baler field efficiency and annual harvest days.

Keywords: corn stover biomass feedstock supply chain, feedstock logistics, techno-economic analysis, Monte-Carlo simulation, sensitivity analysis

2.2 Introduction

Updated billion ton study (BTS) (DOE, 2011) has cited corn (*Zea mays*) stover as the single largest source of agricultural residue in the United States, and has estimated the potential availability of agronomically and ecologically sustainable corn stover feedstock in 2012 to be in the ranges 17-77 and 64-139 million dry Mg (i.e., 19-85 and 71-153 million dry ton) per year, respectively, under normal and more extensive agricultural practices. BTS (DOE, 2011) has further projected the sustainable corn stover residue availability in 2030 to be in the range 56-127 and 200-245 million dry Mg (i.e., 62-140 and 221-271 million dry tons) per year, respectively, under normal and more aggressive agricultural practices. Furthermore, analysis of USDA data for corn production in 2010 (USDA-NASS, 2011), with the assumption that the corn stover removal rate would be the same throughout the U.S., shows around 87% of total U.S. corn stover will be produced in 12 Midwestern states. 20% of this corn stover will be produced in Iowa alone. Thus, there is high likelihood that corn stover biomass will be the primary feedstock choice for the first-generation cellulosic biorefineries in the Midwestern United States. For uninterrupted operation of these plants, year-round supply of corn stover needs to be secured, which will require a robust, efficient and cost-effective feedstock supply chain. This study is focused on evaluating the techno-economics of a corn stover biomass feedstock supply chain having high likelihood of industrial implementation by the first-generation cellulosic biorefineries in the Midwestern U.S. Different components of the supply chain include corn stover harvesting (windrowing and baling), in-field bales collection and stacking at the field-edge, handling and transportation of bales from the field-edge to the distributed central storage facilities and, then, to the biorefinery plant, storage, and finally the audit of nutrients removed during stover collection from the field.

There are several studies proposing different systems for supplying feedstock to cellulosic biorefineries, and estimating their techno-economic requirements; each of which has unique features and capabilities, and makes valuable contribution in enhancing the knowledge base of this area. Most importantly, as the commercial deployment of feedstock supply chain is still to come, each of them should be evaluated and the best fit for a particular instance/situation/location needs to be identified. Some techno-economic studies on corn stover feedstock supply chain, including Sokhansanj et al. (2006, 2010), Hess et al. (2009), Morey et al. (2010) and Turhollow et al. (2008) are briefly discussed here, and their cost estimates for the components balanced with this study are summarized in the following texts. Sokhansanj et al. (2006, 2010) are based on integrated biomass supply analysis and logistics model (IBSAL) (Sokhansanj et al., 2008), which is one of the most commonly used feedstock supply chain models for bio-related processes, and has been developed as a flexible network of dynamic modules that can be connected to form a complete biomass supply chain. This integrated framework allows for a powerful analysis of weather, harvest window, equipment performance, and biomass quality conditions to generate deterministic estimates of cost, external energy use and greenhouse gas emissions of feedstock supply chain. Sokhansanj et al. (2006) estimated the costs of corn stover supply chain following the sequence shredding, baling, stacking, loading to trucks, truck travel, unloading from trucks and stacking, as 40.8 $\$\text{-Mg}^{-1}$ (37.0 $\$\text{-ton}^{-1}$). Sokhansanj et al. (2010) used IBSAL model to perform the techno-economic analysis of corn stover supply chain to fulfill feedstock demand of a dry mill ethanol plant to produce heat and power. They estimated the stover supply requirement to be 140 thousand Mg. Their supply configuration followed shredding, baling (large square bales of dimensions 1.4 m x 1.4 m x 2.4 m), in-field bale collection and field-edge stacking, transportation to and receiving at the biorefinery plant, storage within a covered building with a flat floor and payment to producer as well as 15% of the collection costs as profit assuming the work being done by the custom operator. Overall cost of these operations was 54.9 $\$\text{-Mg}^{-1}$ (49.8 $\$\text{-ton}^{-1}$).

The next techno-economic study on biomass supply chain relevant to this study is “Uniform-Format” feedstock supply system (Hess et al., 2009). This study focuses on supplying different types and formats of biomass feedstock to the biorefinery gate in a uniform format by incorporating feedstock preprocessing steps, including grinding and densification, early in the supply chain at centralized biomass storage/preprocessing depots. This study proposes and has provided thorough techno-economic analysis of pioneer uniform-format biomass supply system, in which feedstock preprocessing (size reduction by grinding) is done at the centralized biomass depots after being stored at the field-edge. As an improvement to this system, they have proposed advanced uniform-format feedstock supply system, which will include two preprocessing operations to enhance the density of feedstock and homogenize qualities before delivery to the biorefinery plant. Further detail on this system has not yet been released. For comparison, they have also performed techno-economic analysis of non-uniform/conventional configuration, in which rectangular corn stover and switchgrass bales are stored at the field-edge after harvest and the feedstocks preprocessing (size reduction) takes place at the biorefinery plant. They have stochastically evaluated biomass supply cost based on the probability distributions of different key parameters. For non-uniform configuration for corn stover feedstock, including grower payment, harvest and collection, storage, transportation and handling, and receiving at the plant, their estimated average cost is 65.6 $\$\text{-Mg}^{-1}$ (59.5 $\$\text{-ton}^{-1}$).

Morey et al. (2010) have estimated the costs for corn stover biomass feedstock supply chain for the heat and power applications. They considered collecting corn stover from the field in round bale format and moving to the local storage sites within 2 mile radius of the field, where bales would be ground and roll pressed before delivering to the plant within 30 mile radius. Morey et al. (2010) uses round bale format and implements preprocessing at the intermediate location, and, thus is not directly comparable to this work; however, this study is of particular interest as it provides one of the viable solutions to current feedstock supply need of the cellulosic biorefineries. Turhollow et al. (2008) have performed the engineering-economic analysis to generate deterministic cost estimates for the production and logistics of bioenergy feedstocks from herbaceous crops and agricultural residues. Although this approach lacks some of the weather and environmental dynamics included in IBSAL, it does provide quality details that can be incorporated into techno-economic models. However, a limiting factor in this approach is a lack of comprehensive productivity parameters to define the biomass equipment systems as well as the dynamic interactions between key cost parameters such as productivity, efficiency, product density, and feedstock quality. They have implemented their cost methodology to estimate harvest, storage, handling and transportation costs of tall fescue harvested as silage, and, thus, their results are not directly comparable to corn stover feedstock considered for this analysis. Nevertheless, this is a useful methodology and should be considered with improvements to analyze supply chain costs.

All of these studies provide viable solutions to feedstock supply chain for future cellulosic biorefineries; however, as is common with most high-level modeling solutions, core assumptions of all these analyses are based on extremely limited datasets. Thus, before commercializing supply chains, it is essential to validate those using production-scale field data. Additionally, these studies (except Hess et al. (2009)) generate single-point deterministic estimates, which doesn't capture the variabilities associated with different parameters and properties of the supply chain. For developing a robust, efficient and cost-effective feedstock supply chain for future cellulosic biorefineries' purposes, it is imperative to know the ranges to which the variabilities associated with different supply chain parameters impact their overall resources and costs requirements. This work addresses both the limitations of these previous studies. The main objective of this study is to stochastically analyze the techno-economics of corn stover feedstock supply chain for a first-generation cellulosic biorefinery in the Midwest using production-scale field data.

The primary feedstock choice for most of the first-generation cellulosic biorefineries planning commercial operation in the Midwest in the near term is corn stover and their rated capacities are in between 76 and 114 million liter per year (MLPY) (i.e., 20 and 30 million gallon per year (MGPY)) (Abengoa, 2013; DuPont, 2013; POET-DSM, 2013). Thus, this analysis considers corn stover biomass feedstock supply chain having high likelihood of industrial implementation by a 114 MLPY (30 MGPY) first-generation cellulosic biorefinery in the Midwest. Probability distribution of the main supply chain parameters are obtained from production-scale experimental field tests conducted in Iowa, and their impacts on the resources and cost requirements for the supply chain are stochastically estimated by employing Monte Carlo simulation method. Additionally, sensitivity analysis is performed to identify the impacts of the pessimistic, most likely and optimistic values of the main supply chain parameters on resources requirements and production cost, and different supply chain parameters are ranked based on their relative influence on these metrics.

2.3 Methodology

2.3.1 Corn stover biomass feedstock supply chain: Systems selection

Figure 2.1 depicts the corn stover supply chain configuration selected for this analysis which includes multi-pass stover harvesting (windrowing and baling), in-field bale collection and stacking at the field edge (referred to as '*stacking*' hereafter), transportation of stover bales from the field-edge to the central storage facilities (referred to as '*storage transport*' hereafter) and, then, to the biorefinery plant (referred to as '*biorefinery transport*' hereafter), storage of stover bales, and finally the audit of nutrients (nitrogen, phosphorus and potassium) removed from the field due to corn stover harvest. Different components are selected based on their likelihood to be implemented by first-generation cellulosic biorefineries in the Midwest.

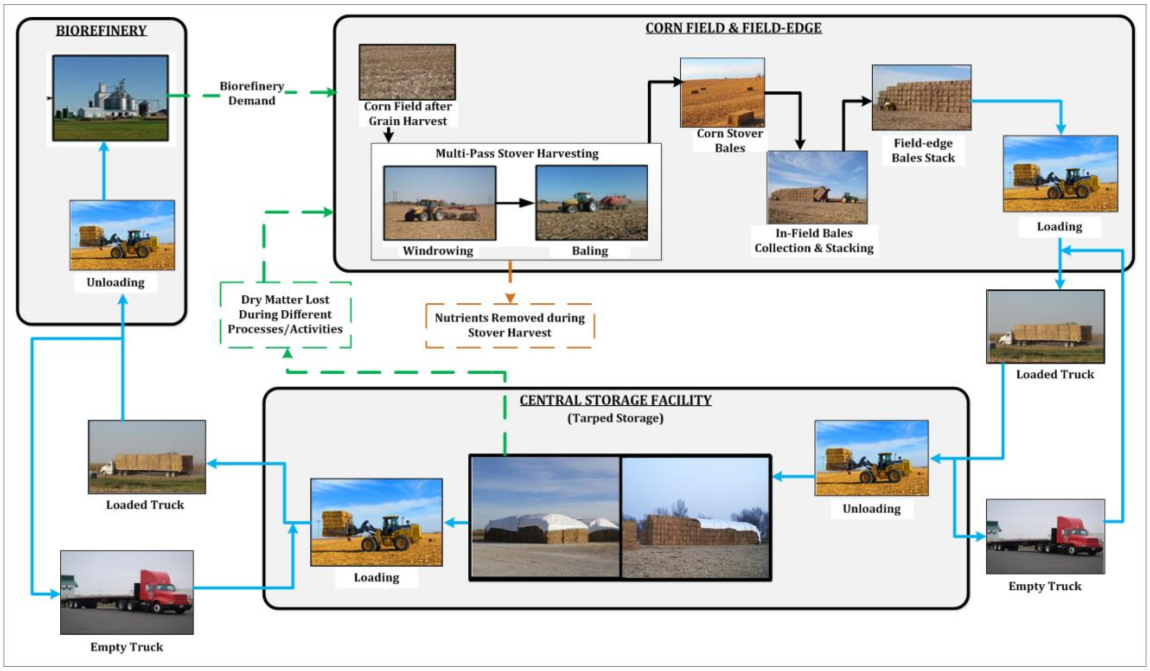

Figure 2.1: Corn stover biomass supply chain for a first-generation cellulosic biorefinery

Overall quantity of stover and the area of land to be harvested for stover are determined based on the corn stover feedstock demand of the biorefinery, percentage of local corn production, producer's willingness in supplying stover to the biorefinery, sustainable rate of stover removal from the field and the overall dry matter loss for the supply chain. Corn stover biomass will most likely be supplied to the biorefinery gate in large rectangular bale format, as suggested by the researchers like Darr and Shah (2012), Sokhansanj and Hess (2009) and Sokhansanj et al. (2010). Thus, this analysis considers large rectangular bales with cross-section 1.22 m (48-in or 4 ft) wide and 0.86 m (34-in or ~3 ft) high, which is common in other baling industries. The length of the bale is controllable by the operators; however, 2.4 m (96-in or 8 ft) is the most common length and can be readily handled with the existing equipment. Alternately, stover can be collected from the field in bulk or round bale format; however, large rectangular bale format is advantageous compared to these in that the bulk format suffers due to low bulk density, thus requiring higher quantities of resources to handle feedstock sufficiently, and large round bales suffer due to complexities associated with mass handling, stacking, transportation, and larger area requirement and shape deformation during storage which compromises safety as well as increases the overall logistical costs.

In the near term, stover will most likely be harvested in the conventional multi-pass platform, in which grain harvest is followed by windrowing and, then, baling; thus, this study considers a multi-pass system for corn stover bale harvesting. In the long term, single-pass stover harvesting systems have the potential to play an increased role in biomass harvesting, mainly due to their advantage in harvesting cleaner stover when compared to that harvested in multi-pass platform. In single-pass systems, both the grain and stover are harvested simultaneously in the same pass through the field. Following stover harvest, bales need to be collected from the field and stacked at the field-edge for further handling. Simultaneous collection of multiple bales from the field is more efficient than the collection of single bale at a time; thus, this analysis considers multiple bale collection system. Multiple bales can be collected from the fields with the use of externally-powered and self-propelled wagons. In this analysis, externally-powered pull-type multi-bale collection wagon is considered as this system was used in the production-scale field tests to collect the data used for this work.

This analysis considers using different teams having fixed numbers of trucks and squeeze loaders for the transportation of bales at both the ends of the biomass supply chain (i.e., storage and biorefinery transports). In the present context, trucks with 14.6 m (48 ft) long and 2.4 m (8 ft) wide flat-bed trailers are common and have been selected for this analysis. Large rectangular bales used in this analysis can be stacked 3-bales high in these trailers, thus, a single truck can haul 36 bales in a single trip. Squeeze loader can handle 6 bales in a single trip without physically piercing the bale surfaces as well as can place the bales perpendicular to the truck trailer, thus, enhancing safety, and has been selected for handling bales entering and leaving storage and biorefinery transports. Alternately, telehandlers can be used for bale handling; however, squeeze loader is preferred because a telehandler can handle only 3 bales in the single trip, physically pierces bales from the side and places the bales parallel to the trailer compromising cost, bale integrity and safety during transportation.

As the next step in the biomass supply chain (Figure 2.1), field-edge stacked bales are loaded to the truck trailers and transported to the central storage facilities where these are unloaded and stored for duration up to more than a year to maintain sufficient inventory and to combat unforeseen uncertainties in stover supply securing year-round biorefinery operation. This study considers storing corn stover bales with an ultraviolet-resistant polyethylene fabric-"tarp" cover, which authors' believe to be the most viable feedstock storage solution for the cellulosic biorefinery in the near term. Feedstock is considered to be stored in 6-bales high, 5-bales wide and 7-bales long stacks, which satisfies the international fire code requirements for biomass storage as indicated by Hess et al. (2009). As discussed in Hess et al. (2009), fire code allows a maximum of 100 ton per stack. Alternative storage methods and their features are discussed in Darr and Shah (2012). After the completion of the desired storage duration, bales are again loaded to the trucks and delivered to the biorefinery plant and the empty truck returns to the storage site. In addition to these operations, nutrients, mainly nitrogen (N), phosphorus (in terms of P_2O_5) and potassium (in terms of K_2O), removed due to stover harvest from the field have also been estimated. These nutrients are essential for plant growth and need to be replenished during subsequent year farming. It is unclear whether a partial stover removal will reduce the amount of organic nitrogen over the long-term thereby needing farmers to replenish N through fertilization. Coulter and Nafziger (2008) have found compensating effects of stover removal on nitrogen fertilizer needs. Although harvesting of stover removes a small amount of N from the field but it reduces the amount of N immobilized in the soil the following year (Johnson et al., 2007). In continuous corn cropping system, removing a portion of the corn stover helps increase N mineralization (Halvorson et al., 2001) and can reduce the overall N fertilizer requirement (Coulter and Nafziger, 2008). On the other hand, studies (Johnson et al., 2010, Edwards, 2011) have suggested that the removal of nutrient through corn stover harvesting carries a significant replacement cost in addition to adverse effects of stover harvesting on soil organic carbon loss (Wilhelm et al., 2004, Blanco-Canqui and Lal, 2009), soil erosion (Mann et al., 2002), and runoff nutrient loss (Wienhold and Gilley, 2010). The complete biomass feedstock supply chain cycle starts with the biorefinery demand, and ends with supplying feedstock to the biorefinery (Figure 2.1). All the pre-storage activities occur within around 30 days each year; and the storage and post-storage events occur throughout the year.

2.3.2 Techno-economic modeling overview

A macro-enabled spreadsheet-based model was developed to perform the techno-economic analysis of corn stover biomass supply chain for a cellulosic biorefinery illustrated in the previous section. Some of the main inputs to the techno-economic model are tabulated in Table 2.1, and their values are mainly obtained from multiple-year production-scale field tests collected from over 16,000 ha (~40,000 acres) of corn fields in Iowa. Major outcomes from this model include the estimates on resources requirements (i.e., labor, machineries, consumables, land, etc.), fuel requirements for the operation of different machineries, and the biorefinery gate delivered stover cost.

Table 2.1: Main inputs to the corn stover biomass supply chain techno-economic model

Parameters	*Values		
	Units	Average	Std. Dev.
α Biorefinery capacity	MLPY (MGPY)	113.6 (30)	
ß Fuel conversion efficiency	L Mg^{-1} (gal ton^{-1})	329.6 (79)	12.5 (3)
σ Overall supply chain DML	%	7.5	2
μ Bale length	cm (in)	243.8 (96)	5.1 (2)
μ Bale width	cm (in)	121.9 (48)	
μ Bale height	cm (in)	86.4 (34)	
μ Bale density	std. kg m^{-3} (std. lb ft^{-3})	166.6 (10.4)	14.4 (0.9)
τ Harvest rate	std. Mg ha^{-1} (std. ton ac^{-1})	3.6 (1.6)	0.9 (0.4)
Φ Harvest window	days yr^{-1}	32	
Φ Windrowers working hours	hr day^{-1}	8.5	
μ Windrower field efficiency	%	70	15
μ Windrower transport efficiency	%	85	5
τ Windrower fuel consumption	L hr^{-1} (gal hr^{-1})	23.1 (6.1)	3.4 (0.9)
Φ Baler working hours	hr day^{-1}	8	
μ Baler field efficiency	%	50	12
μ Baler transport efficiency	%	90	2
τ Baler fuel consumption	L hr^{-1} (gal hr^{-1})	27.6 (7.3)	11.4 (3)
Φ Stacker working hours	hr day^{-1}	11	
τ Stacker productivity (max.)	bales hr^{-1}	65	19.6
μ Stacker field efficiency	%	95	2
μ Stacker transport efficiency	%	90	2
τ Stacker fuel consumption	L hr^{-1} (gal hr^{-1})	17.4 (4.6)	3.8 (1)
Loader fuel consumption	L hr^{-1} (gal hr^{-1})	20.8 (5.5)	5.7 (1.5)
Φ Total satellite storage sites		13	
Φ Storage working days	days yr^{-1}	60	
Φ Storage daily working hours	hr day^{-1}	8	
μ Storage tarping rate	bales/hr	600	100
Φ Storage transport working days	days yr^{-1}	55	
Φ Storage transport daily working hours	hr day^{-1}	8	
Φ Biorefinery transport working days	days yr^{-1}	280	
Φ Biorefinery transport daily working hours	hr day^{-1}	8	
μ Nitrogen removed with stover	kg-N Mg^{-1} (lb-N ton^{-1})	7.7 (15.4)	0.3 (0.6)
μ Phosphorus removed with stover	kg-P_2O_5 Mg^{-1} (lb-P_2O_5 ton^{-1})	2.5 (5.0)	1.1 (2.2)
μ Potassium removed with stover	kg-K_2O Mg^{-1} (lb-K_2O ton^{-1})	12.5 (25)	3.5 (7.0)

* Units and values in parentheses are in U.S. customary units

α Modeling input

ß Humbird et al. (2011); Standard deviation assumed

σ Darr and Shah (2012) suggests 6% DML for tarped storage. Additional 1.5% has been considered for the loss in other processes of the supply chain. Standard deviation for DML is usually high (unpublished data suggests this to be in the range of around 6 percent points); however, for stable supply chain configuration, standard deviation should be minimal. Thus, this analysis considers 2% points standard deviation.

$^{\mu}$ Darr, unpublished data

$^{\tau}$ Data from Peyton (2012)

$^{\Phi}$ Multiple years field experience by Darr research group at ISU

For different processes of the supply chain, annual resources and fuel requirements, as well as costs (i.e., annual working capital) are estimated. In addition to the annual estimates, resources and fuel requirements, as well as costs for biorefinery gate delivered stover to produce unit volume (L) of cellulosic ethanol are also estimated, and are represented as 'per L ethanol produced'. Next, the resources and fuel requirements, as well as costs for delivering a standard weight (Mg) of corn stover feedstock to the biorefinery gate are estimated, and are represented as 'per std. weight (Mg)'. In this analysis 'Standard Weight (Mg)' refers to the weight (Mg) of corn stover with 0% moisture and 8% ash contents. All these estimates account for the dry matter loss (DML) for different processes of the supply chain. Although different estimates are made, results in 'per std. weight (Mg)' basis are mainly discussed throughout this paper. Other results are sometimes discussed in context and are included in the supporting material. Further details of the corn stover biomass supply chain techno-economic model are presented in the following sections.

2.3.2.1 Biorefinery feedstock demand assessment and supply area determination

Annual corn stover biomass feedstock demand of biorefinery is estimated as a function of biorefinery capacity (MLPY) and fuel conversion efficiency (L/Mg). However, to supply sufficient feedstock to the biorefinery, higher amount of stover need to be harvested in order to account for the DML occurring in different processes of the biomass supply chain. So, the actual amount of stover to be harvested to fully meet the biorefinery feedstock demand is the sum of the biorefinery demand and the overall DML for the supply chain. Furthermore, although DML occurs, the bales remain intact up until processed into the biorefinery throat; thus, the quantity of bales to be delivered to the biorefinery is estimated based on the actual amount of stover to be harvested and the bale weight. Bale weight is estimated from its dimensions and density. DML for the supply chain, bale dimensions and density are tabulated in Table 2.1. The feedstock supply area is determined based on the stover quantity to be harvested, proportion of the total land in agricultural production in Iowa, corn production density and the producers' participation in stover harvest. In Iowa, around 86% land is in agricultural production (estimated using information from State Data Center of Iowa, 2013). Additionally, the corn production density in Iowa, estimated using the information from State Data Center of Iowa (2013) and Iowa Department of Agriculture (2013), is around 45% of the overall land in agricultural production. A survey conducted by Tyndall et al. (2011) among Iowa farmers showed that 17% of Iowa's farmers had interest in harvesting their stover as a feedstock for cellulosic biorefineries, with 37% being undecided. Assuming 13% more farmers, among undecided, would decide on harvesting their stover for biofuels production, farmer participation has been taken as 30%.

2.3.2.2 Estimation of resources (machineries, fuel and labor) requirements and costs for windrowing, baling and stacking processes of corn stover biomass supply chain

Quantities of farm machineries required for windrowing, baling and stacking operations are estimated from the total annual working hours required for these operations to harvest and collect stover to fully meet the biorefinery feedstock demand, and the available annual working hours of the farm machineries used in these operations. Total annual working hours required for these operations is estimated based on the overall quantity of stover to be harvested to fully meet the biorefinery feedstock demand and the actual productivities of machineries used for these operations, and the available annual working hours for different farm machineries are estimated based on the available annual working days and daily working hours for different processes (Table 2.1). Maximum productivities of windrower and baler are estimated as the functions of the harvest rate using the regression fits (expression 2.1 for windrower and expression 2.2 for baler) obtained from the field test data collected in Iowa. In both expressions 2.1 and 2.2, harvest rates are in unit of std. ton/ac and the maximum productivities are obtained in unit of std. ton/hr. Actual productivities of different farm machineries are estimated as a product of their maximum productivities, and field and transport efficiencies (Table 2.1).

$$\begin{bmatrix} Maximum\ Productivity \\ of\ Windrower \end{bmatrix} = 5.95 + 9.15 \times \begin{bmatrix} Harvest \\ Rate \end{bmatrix} \tag{2.1}$$

$$\begin{bmatrix} Maximum\ Productivity \\ of\ Baler \end{bmatrix} = 17.55 + 8.75 \times \begin{bmatrix} Harvest \\ Rate \end{bmatrix} \tag{2.2}$$

Field efficiency accounts for the overall downtime during the field operation of machineries and transport efficiency accounts for the time required to move the machineries from one field to the other. Iowa State University researchers (Peyton (2012) and Covington (2013)) have provided details of the procedures for productivities and efficiencies estimation for different machineries. Their approach is different from the published machinery management data sources (ASABE, 2011a, 2011b), which were generated before the advent of biobased economy and, thus, do not essentially represent the true capacity of today's equipment designed specifically for collecting huge quantity of biomass for biorefineries. Peyton (2012) and Covington (2013) used embedded controller area network (CAN) and GPS data logging systems (CyCAN data loggers) to collect specific machinery parameters. Darr (2012) includes the further details of CyCAN data loggers. Labor requirements (in terms of annual hours) are estimated considering the requirement of 1 operator for different machineries.

Fuel usage for the operation of different machineries comes from the field data collected by the Iowa State University researchers by conducting production-scale field tests in Iowa, details of which are included in Peyton (2012). The data were collected using CyCAN logger which records the fuel rates (L hr^{-1}) for different machineries and their average fuel consumption values are tabulated in Table 2.1. Annual fuel consumption (L yr^{-1}) and the fuel consumption for a std. weight (Mg) of biorefinery gate delivered stover are estimated using the annual working hours and productivities of different machineries.

Costs for windrowing, baling and stacking operations are estimated as fixed ownership costs of farm machineries and the variable operating costs for different processes. Ownership costs of farm machineries occur annually regardless of machinery use and are considered as fixed costs. In this analysis, ownership costs of farm machineries have been broadly classified into two categories: capital recovery cost and the other ownership costs including costs for taxes, insurance and housing, following the methodology suggested by Edwards (2009). Capital recovery cost accounts for the depreciation on farm machineries as well as the interest rate on the investment. Depreciation in the value of farm machinery over its total use period is calculated as the difference between its purchasing price and the salvage value. Purchasing price has been estimated accounting for the dealer's discount at 15% on the list price. List price of the farm machineries used for windrowing, baling and stacking operations are included in Table 2.2, and are based on the equipment purchasing experiences of the authors of this work.

Salvage values of the machineries after their planned years of use have been estimated as percentage of their list prices included in Table 2.2. These values are mainly based on authors' experiences with stover harvesting in an industrial setting, and differs from other published suggested values in ASABE standards for agricultural machinery management (ASABE, 2011a; ASAE 2011b), which are mainly based on the small-scale stover harvesting efforts for animal feeding and bedding, and on the auction sale values of used farm machineries from 1984 to 1993, making these basically outdated. After estimating depreciation and salvage value, capital recovery cost is estimated using expression 2.3 (Edwards, 2009) using capital recovery factor (Table 2.2) and the adjusted interest rate of 5%, which is the difference of the actual interest rate (i.e., 8% for this analysis) and the inflation rate (i.e., 3% for this analysis). Capital recovery factors and the interest rates used in this study are taken from Edwards (2009). For the other ownership costs, costs for the insurance and housing of the farm machineries were each estimated at 0.5% of their purchasing prices, as suggested by Edwards (2009). In Iowa, there is no tax on farm machineries.

$$\begin{bmatrix} Capital \\ Recovery\ Cost \\ (\$/Year) \end{bmatrix} = \left[\begin{pmatrix} Capital\ Recovery \\ Factor \\ (\%) \end{pmatrix} \times \begin{pmatrix} Total \\ Depreciation \\ (\$/Useful\ Life) \end{pmatrix}\right] + \left[\begin{pmatrix} Adjusted \\ Interest\ Rate \\ (\%) \end{pmatrix} \times \begin{pmatrix} Total \\ Salvage\ Value \\ (\$/Useful\ Life) \end{pmatrix}\right] \qquad (2.3)$$

[α]Table 2.2: Details of farm machineries used for windrowing, baling, and in-field bale collection and stacking operations.

Farm Machineries	Make	Model	[Φ]List Price ($)	[ß]Useful Life	[Γ]Planned Use Years	[δ]Salvage Value (%)	[ε]Capital Recovery Factor (%)	[Θ]R&M Factor (%)
Windrower	Hiniker	5620	35,000	2,000 hr	4	15	28.2	27
Baler	AGCO/ Massey Ferguson	2170XD	140,000	75,000 bales	7	25	17.3	35
Stacker	ProAG	16K Plus	94,000	100,000 bales	5	15	15.5	49

[α] Trade names are mentioned solely to provide specific information and do not imply endorsement of the products by the authors or Iowa State University and the research collaborators.

[Φ] The list prices are based on the equipment purchasing experiences of the authors of this work. Actually, purchasing price is usually around 15% less than the list price.

[ß] The useful lives are based on the field experiences of the authors of this work.

[Γ] Life is estimated based on the actual annual use of the machineries during Iowa State University production-scale biomass collection research.

[δ] Salvage value (% of list price of new machinery) for different farm machineries have been selected based on the experiences of the authors of this work.

[ε] Capital recovery factors are taken from Edwards (2009), and is based on the adjusted interest rate (i.e., actual interest rate - inflation rate) on investment and the planned years of use of different machineries. In this analysis, actual interest rate has been taken as 8% and the inflation rate as 3%.

[Θ] R&M factors (% of list price of new machinery) are taken from Edwards (2009), and are used to estimate the repair and maintenance costs for different farm machineries over their useful life

The second cost category is the operating cost, which accounts for the costs for all the activities related to the functioning of windrowing, baling and stacking processes of the supply chain. Unlike fixed ownership costs, operating costs are variable depending upon the amount of operating durations for different processes. For all three processes, ownership costs discussed earlier were just for the windrower, baler and stacker attachments, which need tractors to power and drive through the field. For powering and driving the windrower, baler and stacker, tractors of 105, 186 and 168 kW (i.e., 140, 250 and 225 hp), respectively, were used. This analysis considers leasing tractors against purchasing as huge quantities of tractors are required for different processes, and, thus, if purchased, there is additional need to repair and maintain as well as house them throughout the year although annually required for only few months. Additionally, tractors are historically being used for different purposes and are easy to lease in sufficient quantities, in contrast to the windrower, baler and stacker attachments, which are not available for rent in large quantities. Lease rates of tractors, excluding labor and fuel costs, for windrower, baler and stacker implements are based on the production-scale corn stover supply chain research experience at Iowa State University, and were 27.5, 50 and 45 $\$\text{-hr}^{-1}$, respectively, for 105, 186 and 168 kW (i.e., 140, 250 and 225 hp) tractors. The overall tractor rental costs for different operations are estimated using the hourly rates, overall annual use hours, and the productivities and efficiencies of these machineries.

Labor and fuel costs are the next operating costs, and are estimated based on the annual labor requirements and the fuel consumption for the operation of different farm machineries. Labor rates are taken as 14 $\$\text{-hr}^{-1}$ for the operation of windrower, and 18 $\$\text{-hr}^{-1}$ for the operation of baler and stacker. Additionally, 20% overhead has been considered in labor wages in order to account for the benefits. Fuel costs are estimated based on the 3-year (2010-2012) average retail price of no. 2 diesel in the Midwestern United States, which is 0.94 $\$\text{-L}^{-1}$ (3.56 $\$\text{-gal}^{-1}$) (EIA, 2013), and the fuel consumed by different farm machineries, explained earlier. Repair and maintenance (R&M) cost is the next operating cost category and occurs mainly due to the need of routine maintenance of machineries. R&M cost is highly variable and depends upon the type of machinery, geographical region, management policies and operator skills. For this analysis R&M costs for windrower, baler and stacker attachments over their useful lives are estimated as the fraction of the list price of the new machineries, as suggested by Edwards (2009). Useful lives and R&M factors for different machineries are tabulated in Table 2.2. Useful lives of different machineries are based on the production-scale field tests by Iowa State University researchers and R&M factors are taken from Edwards (2009).

Cost of consumables for different processes is the next operating cost category. Among windrowing, baling and stacking operations, string used by balers is the only consumable, and, thus, is represented as 'string cost' for baling operation. A bale is tied along the top, sides and bottom surfaces 6 times. Thus, the overall string requirement is estimated from this information, and the string cost is estimated using the retail string purchase cost of $18.8 per 1000 m (i.e., $5.71 per 1000 ft) of string. The final operating cost category is overhead and administrative cost (admin cost), which includes the costs of activities which are not directly related to the production activities, such as administrative support, logistical coordination, purchasing, travel to different sites, hospitality, emergency breakdowns, occasional per diem food and lodging requirements, and the other unforeseen activities. Windrowing, baling and stacking operations need to be accomplished within a short harvest window of around 30 days yr^{-1}, thus, to avoid any delay in these activities resulting in the loss of biomass, their admin costs have been estimated at 20% of the overall ownership and operating expenses.

2.3.2.3 Estimation of resources (machineries, fuel and labor) requirements and costs for the transportation operation at both the ends of corn stover biomass supply chain (i.e., storage and biorefinery transports)

For storage and biorefinery transports, each team has been considered to operate with 3 and 8 trucks (with 14.6 m (i.e., 48 ft) long and 2.4 m (i.e., 8 ft) wide flat-bed trailers), respectively. Despite the need to haul same number of bales, number of trucks per team for storage transportation has been taken less than those for the biorefinery transport, mainly due to the spread of fields from which bales need to be collected during storage transport, thus, more teams with less number of trucks can be employed. In contrast to this, during biorefinery transport, bales need to be hauled from fixed number of centralized storage locations. In addition to this, Gutesa (2013) suggests 1 loader at each end (delivering and receiving ends) of the transportation chain can be optimally utilized for handling 3 trucks, and 2 loaders at each end for 8 trucks. Thus, for loading and unloading bales to/from the truck trailers for storage and biorefinery transports, each team have been considered to operate, respectively, with 2 and 4 squeeze loaders (i.e., 1 and 2 at each delivering and receiving ends of the transportation chain). Furthermore, loading and unloading operations are considered identical due to the same machineries involved for both of these operations.

Total trucks and squeeze loaders required for transferring stover at both the ends of the supply chain is estimated as a product of trucks and loaders per team and the total teams. Number of trucks and loaders per team are fixed, and the total number of teams required for facilitating transportation is estimated as a ratio of total annual truck trips requirement for completely hauling biomass, and the product of trucks per team and total trips made by a single truck each year. Total annual truck trips requirement is estimated from total annual biomass supply and the truck capacity, and the annual trips made by a single truck is estimated from truck productivity (trips hr^{-1}) and their annual working duration. Truck productivity is estimated as a function of the average one-way travel distance between the two locations using the regression fit (expression 2.4) obtained from the field test data collected over distances 1.6 to 48 km (i.e., 1 to 30 mi), thus, this equation is valid over these distances.

$$\begin{bmatrix} Truck\ Productivity \\ (Truck\ Trips/hr) \end{bmatrix} = 0.96 \times e^{(-0.03\times(One-way\ travel\ distance))} \tag{2.4}$$

Average one-way travel distance is estimated in different ways for the storage and biorefinery transports. For storage transport, average one-way travel distance is estimated as a function of overall feedstock collection area, number of storage sites and the winding factor of roads. The overall stover collection area of biorefinery is divided into the given number of storage sites, each representing the localized collection area for a central storage facility. Both the overall feedstock collection area of the biorefinery and the areas of the collection regions for different storage sites are assumed to be circular in shape. Thus, the average one-way travel distance between the field-edge and the central storage facilities is estimated as the radius of the half of the area of the collection region of a storage facility scaled with winding factor of the roads (expression 2.5). For biorefinery transport, stored biomass from different central storage facilities are transported to the central biorefinery plant, which has been assumed to lie at the center of overall stover collection region. Thus, the shortest distance between the biorefinery plant (assumed to lie in the center of the overall feedstock collection area of the biorefinery plant) and the farthest distributed central storage facility (assumed to lie at the center of the feedstock collection radius for central storage facility) is estimated as the difference of the radius of overall biorefinery feedstock collection area and that of one satellite storage facility. Area with this distance as radius gives the inner area on circumference of which rests the farthest satellite storage sites. Thus, for the transportation of stored stover at this end of the supply chain, one-way travel distance is estimated as radius of the half of this (inner) area scaled with the winding factor (deduced to expression 2.6). The winding factor for the storage transport is usually higher than that of the biorefinery transport mainly due to the difference in the road types for these two cases. For storage transport, stover is collected from the fields and hauled to the central storage facilities, traveling mainly over the county roads with higher number of turns; however, for biorefinery transport, stored stover is moved from the central facilities to the biorefinery plant, traveling mainly over the state highways, which, comparatively, have less turns. Gutesa (2013) has determined the winding factor of roads for transferring biomass between the fields and the central storage facilities as 1.4, which has been used for storage transportation in this analysis. For biorefinery transportation, winding factors of roads has been taken as 1.3.

$$\begin{bmatrix} One\ Way\ Travel\ Distance \\ for\ Storage\ Transport \end{bmatrix} = [Winding\ Factor] \times \sqrt{\frac{\left[\frac{Overall\ Storage\ Collection\ Area}{Number\ of\ Satellite\ Storage\ Sites}\right]}{\frac{2}{\pi}}} \quad (2.5)$$

$$\begin{bmatrix} One\ Way\ Travel\ Distance \\ for\ Biorefinery\ Transport \end{bmatrix} = [Winding\ Factor] \times \frac{\begin{bmatrix} Radius\ of \\ Overall\ Bioreinfery \\ Feedsock\ Collection\ Area \end{bmatrix} - \begin{bmatrix} Radius\ of \\ a\ Satellite\ Storage\ Site \end{bmatrix}}{\sqrt{2}} \quad (2.6)$$

Costs for storage and biorefinery transports are estimated as trucking and handling costs. Handling cost accounts for the costs incurred during loading and unloading stover bales to and from the trucks at the two ends of storage and biorefinery transports. Trucks and squeeze loaders used for both storage and biorefinery transports are considered to be rented, thus, all the costs incurred for these operations are variable operating costs. Trucking costs are evaluated at the truck rental rates, including fuel cost and driver’s wage, of 100 and 75 $\$\text{-hr}^{-1}$, respectively, for the storage and biorefinery transports. The truck rental rate is higher for storage transportation mainly due to their high demand during the short operating window in the harvest season. Although unit truck rental costs for both the storage and biorefinery transports include fuel and labor costs, fuel and labor requirements for the operation of trucks are estimated separately. Fuel consumption for the truck operation was estimated using GREET Fleet Footprint Calculator (ANL, 2013), and was 0.38 L km^{-1} (i.e., 0.16 gal mi^{-1}). Labor requirement is estimated based on the number of trucks considering one operator for each truck.

Handling costs are estimated at the squeeze loader rental rate of 47.5 \$-hr^{-1} for both the storage and biorefinery transports. Loader rental rate doesn't include the operator and fuel costs; thus, these are separately estimated. Labor cost is estimated considering 1 operator for each squeeze loader, total numbers of loaders, annual operating duration, capacities, productivities, and wage. Loader labor wage has been taken as 18 \$-hr^{-1} and 20% labor wage overhead. Fuel consumption data for squeeze loader operation was collected using CyCAN logger in the same way as explained in the previous section, and has been tabulated in Table 2.1. This information, along with loader productivity (estimated from truck productivity), capacity, retail diesel price and overall usage duration are used to estimate the fuel cost for handling operation. The final cost category for trucking and handling operations of storage and biorefinery transports; i.e., admin cost (administrative and overhead costs) has been estimated at 10% of these costs. The admin cost is lower than field operations due to the reduced complexities and logistical requirements of this operation.

2.3.2.4 Estimation of resources requirements and costs for storage of corn stover bales

The overall feedstock storage footprint area is estimated from the total number of bales to be stored annually, height of bale storage stacks and the footprint area of a single bale. Actual feedstock storage area is usually bigger than the footprint area for enhancing accessibility as well as reducing potential fire hazards possible due to self-heating of stored bales or other unpredictable accidents. Additional area also eases in decision making for inventory management allowing the site managers to prioritize the order of the batch of bales to remove from the storage. In addition to these, Hess et al. (2009) has indicated that the biomass storage stack is limited by international fire code, which allows a maximum of 90.7 Mg per stack (i.e., 100 ton per stack) and requires a minimum of 3 m (i.e., 10 ft) between adjacent stacks. Assuming the average bale weight of around 0.45 Mg (i.e., 0.5 ton), the total bales in each stack is around 200. Taking 210 bales per stack, and leaving 6 m (i.e., 20 ft) between the adjacent stacks, additional area requirement for biomass storage is around 171% of the footprint area. This analysis considers 200% additional area to fulfill international fire code requirements and for the other reasons discussed earlier. Thus, the actual area is 3 times higher than that of the footprint area.

Average cash rental rate for cropland in Iowa in 2012 was 580 $\$$-ha^{-1} (i.e., 235 $\$$-ac^{-1}) (Edwards, 2012), however, a text message survey of farmers and ranchers conducted by Farm Journal found the cash rent auction for land in Iowa in 2011 was as high as 1310 $\$$-ha^{-1} (i.e., 530 $\$$-ac^{-1}) (Russell, 2012); thus, this analysis considers the land rental rate of 1235 $\$$-ha^{-1} (i.e., 500 $\$$-ac^{-1}) to estimate the land cost. For tarped bale storage, rock surfaces provide protection from moisture movement into the bottom layer of bales and levels the grounds such that water can move away from bale stacks (Darr and Shah, 2012). This analysis considers laying rock on the storage footprint and an additional 20% area, and the rock cost has been evaluated at 1.4 $\$$-m^{-2} (i.e., 0.13 $\$$-ft^{-2}) for the useful life of 5 years. In addition to land and rock costs, tarp cost for covering the top of the bale stacks is estimated based on the storage footprint area and the tarping rate of 2.47 $\$$-m^{-2} (i.e., 0.23 $\$$-ft^{-2}) of storage footprint (Darr and Shah, 2012).

This analysis considers the execution of bale storage operation at different satellite storage facilities in teams. Total number of teams required is estimated from the annual working hour requirement for completely establishing tarp covers on bale stacks and an additional 20% time for annual bale stacks maintenance, annual working duration for storage (annual days and daily hours, Table 2.1), and the number of persons in each team. Total annual hour requirement for establishing tarp covers on bale stacks is estimated based on the overall quantity of bales to be stored each year and the tarping rate. Production-scale field test data suggest four people working in a team can cover 600 bales in an hour. Total number of persons required for annual establishment and maintenance of tarped storage is estimated as the product of the total teams and the number of persons in each team. Additionally, based on the total number of persons, and annual working duration for storage, total labor requirement (in terms of hour) is estimated. And, the storage labor cost has been estimated using labor wage of 12 $\$$-hr^{-1} and 20% overhead. All the storage costs; i.e., land, rock, tarp and labor costs are operating or variable costs. The final storage cost category, i.e., admin cost has been estimated as 20% of the total of land, rock, tarp and labor costs.

2.3.2.5 Estimation of quantities of nutrients removed from the fields with stover harvest and the costs of replenishment

Quantity of Nitrogen (N) removed from the field with stover collection is determined from the results of ultimate analysis performed using ASTM Standard D5373 (ASTM, 2008). Quantities of phosphorus (in form of P_2O_5) and potassium (in form of K_2O) removed from the field due to stover harvest are estimated from the results of mineral ash analysis (performed using ASTM Standard D3682 (ASTM, 2006)) on ash samples (obtained using ASTM Standard D3174 (ASTM, 2008)) of field harvested stover. Field test results suggest that, on an average, 7.7 kg-N, 2.5

kg-P_2O_5 and 12.5 kg-K_2O are removed along with a dry and ash-free Mg of stover collected from the field. Assuming all the nutrients removed from the field during stover harvest would be replenished, costs of nitrogen, phosphorus and potassium replenishment were, respectively, estimated at the rates of 1.28, 1.06 and 1.10 $-kg^{-1} (0.58, 0.48 and 0.50 $-lb^{-1}) of nutrients (Duffy, 2013). Costs of replenishing all the nutrients removed from the fields during stover harvest are operating or variable costs. Unlike other processes, admin cost has not been added to this category as the system boundary for feedstock logistics only includes the estimation of the quantities of nutrients removed from the field. Admin cost occurs during nutrients application to the field, which is the part of the feedstock production process, and is out of the scope of this analysis.

2.3.2.6 Overall cost of corn stover feedstock supply chain

Overall cost of corn stover feedstock supply chain includes all the costs discussed so far, and an additional 10% admin cost for providing the managerial and administrative supports to the overall supply chain securing its smooth functioning.

2.3.3 Monte Carlo simulation and sensitivity analysis

Monte Carlo simulation (500 iterations) has been performed to understand the impact of the variabilities of different input parameters on the outcomes of this analysis or to generate the probability distribution of the results. Inputs for Monte Carlo simulations are based on production-scale field tests and possess normal probability distribution functions. Although this model is supplied with more than 100 inputs, only those tabulated with standard deviation in Table 2.1 are used to provide probability distribution functions for Monte Carlo simulation. Other inputs are supplied as a single value. Main outputs of this analysis are total units of machineries required for different processes, labor and fuel requirements, and the costs of different processes. All the results of this analysis are presented with 95% confidence interval (CI) on mean and 95% central range (CR) of the output data. In addition to these, histograms along with cumulative distribution function (CDF) graphs for different outputs discussed in the results section of this paper are included in the supporting material.

Sensitivity analysis was performed to determine the influence of 50 different inputs parameters (Table 2.3) on the feedstock supply and resources requirements, and production cost of the corn stover biomass supply chain and its different components. The pessimistic, most likely and optimistic values of different parameters were based on data from production-scale corn stover biomass supply chain research; and is different from the many other studies in the literature that uses the ranges of values for sensitivity analysis as a fixed percentage of the input variables. Additionally, different parameters are ranked based on the relative influence of their extreme values on the output metrics (i.e., biomass supply and resources requirements, and production cost). It should be noted that sensitivity analysis has been conducted to gauge the relative influence of 50 different supply chain parameters (Table 2.3), however, only parameters influencing different output metrics are shown in different figures throughout this chapter and the associated supporting materials. Both Monte Carlo simulation and sensitivity analysis are performed in macro-enabled spreadsheet, and the necessary statistical analyses on output data to generate histograms and CDF graphs are performed using JMP software (SAS, 2013).

Table 2.3: Different parameters for the sensitivity analysis and range of their pessimistic, most likely and optimistic values

Parameters	*Units	*Ranges of Input Parameters		
		Pessimistic	Likely	Optimistic
Fuel conversion efficiency	L (clean Mg)$^{-1}$ (gal (clean ton)$^{-1}$)	292.1 (70)	329.6 (79)	367.2 (88)
Dry matter loss (DML)	%	10.0	7.5	5.0
Harvest rate	std. Mg ha^{-1} (std. ton ac^{-1})	2.7 (1.2)	3.6 (1.6)	4.5 (2)
Ag production in Iowa	% of Total Iowa area	80.0	86.0	90.0
Density of corn	%	35.0	45.0	55.0
Producer participation	%	20.0	30.0	40.0
Bale length	cm (in)	213.4 (84)	243.8 (96)	274.3 (108)
Bale height	cm (in)	86.4 (34)	86.4 (34)	91.4 (36)
Bale density	std. kg m^{-3} (std. lb ft^{-3})	144.2 (9)	166.8 (10.4)	192.2 (12)
Harvest days	days	24	32	40
Windrower working hours	hr day^{-1}	7	8.5	10
Baler working hours	hr day^{-1}	7	8	9
Stacker working hours	hr day^{-1}	8	11	12
Fuel cost	\$ L^{-1} (\$ gal^{-1})	1.1 (4)	0.9 (3.6)	0.8 (3)
Interest rate	%	8.0	8.0	6.0

Parameters	*Units	*Ranges of Input Parameters		
		Pessimistic	Likely	Optimistic
Windrower fuel consumption	L hr^{-1} (gal hr^{-1})	34.1 (9)	23.1 (6.1)	18.9 (5)
Baler fuel consumption	L hr^{-1} (gal hr^{-1})	37.9 (10)	27.6 (7.3)	18.9 (5)
Stacker fuel consumption	L hr^{-1} (gal hr^{-1})	28.8 (7.6)	17.4 (4.6)	13.6 (3.6)
Storage transport: Loader fuel consumption	L hr^{-1} (gal hr^{-1})	24.6 (6.5)	20.8 (5.5)	17 (4.5)
Biorefinery transport: Loader fuel consumption	L hr^{-1} (gal hr^{-1})	24.6 (6.5)	20.8 (5.5)	17 (4.5)
Nitrogen removed (Quantity)	kg-N (clean $Mg)^{-1}$ (lb-N (clean $ton)^{-1}$)	9 (18)	7.7 (15.4)	6.5 (13)
Potassium removed (Quantity)	kg-K_2O (clean $Mg)^{-1}$ (lb- K_2O (clean $ton)^{-1}$)	15 (30)	12.5 (25)	10 (20)
Phosphorus removed (Quantity)	kg-P_2O_5 (clean $Mg)^{-1}$ (lb-P_2O_5 (clean $ton)^{-1}$)	3.5 (7)	2.5 (5)	1.5 (3)
Nitrogen (Unit cost)	\$-(kg-N)$^{-1}$ (\$-(lb-N)$^{-1}$)	1.4 (0.6)	1.3 (0.6)	1.2 (0.5)
Potassium (Unit cost)	\$-(kg-K_2O)$^{-1}$ (\$-(lb-K_2O)$^{-1}$)	1.2 (0.6)	1.1 (0.5)	1 (0.5)
Phosphorus (Unit cost)	\$-(kg-P_2O_5)$^{-1}$ (\$-(lb- P_2O_5)$^{-1}$)	1.2 (0.5)	1.1 (0.5)	0.9 (0.4)
Windrower field efficiency	%	60	70	80
Windrower transport efficiency	%	75	85	95
Windrower tractor rental cost	\$-hr^{-1}	30	27.5	25
Baler field efficiency	%	40	50	60
Baler transport efficiency	%	85	90	95
Baler life (Planned use)	bales	60,000	75,000	100,000
Baler tractor rental cost	\$-hr^{-1}	55	50	45
Stacker theoretical productivity	bales hr^{-1}	50	65	80
Stacker field efficiency	%	90	95	97
Stacker transport efficiency	%	85	90	95
Stacker tractor rental cost	\$-hr^{-1}	50	45	40
Stacker life (Planned use)	bales	80,000	100,000	120,000
Storage transport: Transport window	days yr^{-1}	40	55	70
Storage transport: Trucking working hours	hr day^{-1}	7	8	9
Storage transport: Truck rental cost	\$-hr^{-1}	125	100	75
Storage stack height	bales	4	6	6
Tarp maintenance time requirement	% of Total Tarping Time	50	20	10
Storage working days	days yr^{-1}	40	60	80
Tarp life	yr	1	2	2
Storage land rental cost	\$-ha^{-1} (\$-ac^{-1})	2,470 (1,000)	1,235 (500)	741 (300)
Biorefinery transport: Transportation days	days yr^{-1}	200	280	300
Biorefinery transport: Trucking working hours	hr day^{-1}	7	8	9
Biorefinery transport: Truck rental cost	\$-hr^{-1}	100	75	65
Number of satellite storage facilities	Number	6	13	20

* Units and values in parentheses are in U.S. customary system of units.

2.4 Results and Discussions

2.4.1 Biorefinery feedstock demand and supply area

Means with 95% confidence interval (CI) and 95% central range (CR) for biorefinery feedstock demand, harvest supply and the supply area are included in Table 2.4. Mean annual corn stover feedstock demand of a 114 MLPY (30 MGPY) biorefinery plant is estimated to be around 374 thousand std. Mg (~413 thousand std. ton). Due to the dry matter losses occurring in different processes of the supply chain, supplying this amount of stover to the biorefinery, on an average, requires around 404 thousand std. Mg (~445 thousand std. ton) of stover harvested each year. Due to the variabilities in different supply chain parameters, 95% central range for biorefinery feedstock demand and annual harvest supply falls between 350 and 400, and 375 and 435 thousand std. Mg, respectively (Table 2.4). These spreads in the biorefinery supply requirements are mainly due to the variabilities in the biorefinery-specific parameters. Biorefinery stover demand is entirely dependent upon the fuel conversion efficiency (L Mg^{-1} of stover), and the annual harvest supply is dependent on this parameter and DML for the stover supply chain (Figure 2.2). These stover requirements of a biorefinery can be decreased with increase in fuel conversion efficiency and reduction in DML.

[Γ] Table 2.4: Summary of annual biorefinery feedstock demand and supply requirements

	Biorefinery Demand (std. Mg/ Year)	Harvested Stover (std. Mg (har.)/ Year)	Bale Supply (Bales/ Year)	Harvest Area (ha)	Supply Area (ha)	Supply Counties
[α] 95% CI on Mean	373,702 ± 1,223	403,926 ± 1,329	952,284 ± 8,210	126,448 ± 5,556	1,053,733 ± 46,297	7.1 ± 0.3
[ß] 95% CR	(346,859, 402,945)	(377,012, 434,646)	(791,708, 1,153,614)	(75,264, 250,731)	(627,198, 2,089,425)	(4.2, 14.0)

[Γ] 95% CI on mean and 95% CR results are generated through Monte Carlo simulation (500 iterations)

[α] Values are mean ± upper and lower bounds for 95% CI on mean

[ß] Values within parentheses are lower and upper bounds of 95% CR

Fulfilling biorefinery stover demand, on an average, will require around 0.95 million rectangular bales (95% CR: 0.8-1.15 million). This suggests that 95% of the time in optimistic working conditions (i.e., better performance of different supply chain parameters) the overall bale requirement of biorefinery can be reduced by around 150 thousand units; while in the pessimistic working conditions, annual bale requirements can increase by around 200 thousand units. To put this into perspective, just to transport 50 thousand bales, around 1,400 truck trips are required. Assuming 280 days transportation period, reducing annual bale requirements by 150 thousand units can save around 15 truck trips each day, and increasing by 200 thousand units would require an extra 20 truck trips each day. In addition to transportation, bale quantities impact all the other post-harvest components of the supply chain. Analyzing the sensitivity of the bale quantity requirement for biorefinery on different supply chain parameters reveal that it is the most sensitive to the bale density (Figure 2.2), as with increase in the density of bales with fixed dimensions, their weights increase, which lead to the reduction in the required quantities. The other supply chain parameters impacting the overall bale supply requirements of biorefinery are bale length, followed by the fuel conversion efficiency, bale height and DML (Figure 2.2). These different parameters impact overall bale supply requirements either by changing the weights of bales (caused by bale density, length and height) or by reducing the overall feedstock demand of the biorefinery (caused by fuel conversion efficiency and DML).

To fulfill feedstock demand of an Iowa-based cellulosic biorefinery, stover, on an average, needs to be collected from around 126 thousand (95% CR: 75-250 thousand) ha of land area in corn (Table 2.4). Furthermore, considering 30% producer participation, the average stover supply area is around 1 million ha (95% CR: 0.6-2 million) ha (Table 2.4). The corn stover harvest area is highly influenced by the harvest rates of stover from the corn fields, fuel conversion efficiency and DML; however, the overall stover supply area depends on producer participation, density of corn in agricultural lands and agricultural production in Iowa in addition to the parameters influencing harvest area requirement (Figure 2.2).

Figure 2.2: Sensitivities of annual biorefinery stover demand, annual stover harvest requirement, annual bale supply requirement, actual harvest area and overall stover supply area for a 114 MLPY (30 MGPY) cellulosic biorefinery on the supply chain system parameters

2.4.2 Machineries, Labor and fuel requirements

Table 2.5 summarizes the annual farm machineries requirements for corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery. Working windows for different operations have also been included in Table 2.5 as annual machineries quantities requirements are directly related to the available working durations. Windrowing, baling and stacking operations need to be accomplished within a narrow harvest window, thus, the required quantities of machineries for these operations are usually higher. Despite higher field efficiency and daily operating duration of windrowers when compared to those of balers, their required number is higher, mainly due to their lower theoretical maximum productivity (comparing expressions 2.1 and 2.2). The productivity of windrower is lower than that of the baler as windrowing involves chopping stover from the field and aligning them in windrows requiring time-intensive mechanical task in field, whereas during baling operation stover is picked from the windrows while passing through the field and bale packaging process takes place mechanically within the baler. The field efficiency of balers is lower than that of windrowers primarily due to increased downtime during baling operation resulting from the clogging of stover within the baling chamber (Covington, 2013). In contrast to both the windrowing and baling operations, stacking involves less mechanical operations. Stackers collect bales scattered around the field in an “on-the-go” basis and move them to the field edge, thus, operate at a higher speed and for extended hours resulting in the requirement of lesser quantities than windrowers and balers despite working days being the same.

Table 2.5: Annual farm machineries requirements for corn stover feedstock supply chain of a 114 MLPY (30 MGPY) biorefinery plant

Types of Farm Machineries	Annual Working Days (days/year)	Daily Working Hours (hr/day)	ᴦFarm Machineries Requirements	
			α95% CI on Mean	ß95% CR
Windrowers with tractors	32	8.5	149 ± 4	(84, 278)
Balers with tractors		8.0	134 ± 3	(79, 227)
Stackers with tractors		11.0	56 ± 2	(30, 121)
Trucks for storage transport	55	8.0	85 ± 1	(69, 107)
Loaders for storage transport			56 ± 1	(45, 71)
Trucks for biorefinery transport	280	8.0	25 ± 0	(20, 35)
Loaders for biorefinery transport			12 ± 0	(9, 18)

ᴦ 95% CI on mean and 95% CR results are generated through Monte Carlo simulation (500 iterations)

α Values are mean ± upper and lower bounds for 95% CI on mean

ß Values within parentheses are lower and upper bounds of 95% CR

The 95% central range for the windrowers, balers and stackers requirements is highly spread due to the variabilities associated with different supply chain parameters. Analyzing the sensitivity of different system parameters on the quantities requirements of these farm machineries (Figure 2.3) suggest that these are mainly influenced by the available working durations (i.e., harvest window and daily working hours for all three operations), actual productivities (i.e., function of harvest rate, and field and transport efficiencies), and the parameters that could directly reduce the feedstocks harvest need (i.e., DML and fuel conversion efficiency). In addition to these, stacking operation is impacted by the bale-specific parameters (i.e, density, length and height), as this operation involves handling individual bale units. Thus far, adjusting working duration is beyond human capability as it depends on weather conditions and working in the night is unsafe as well as biomass is usually wet in early morning hours; however, improving fuel conversion efficiency and machineries' productivities, enhancing physical properties of bales, and reducing DML can significantly reduce the requirements for overall quantities of different farm machineries.

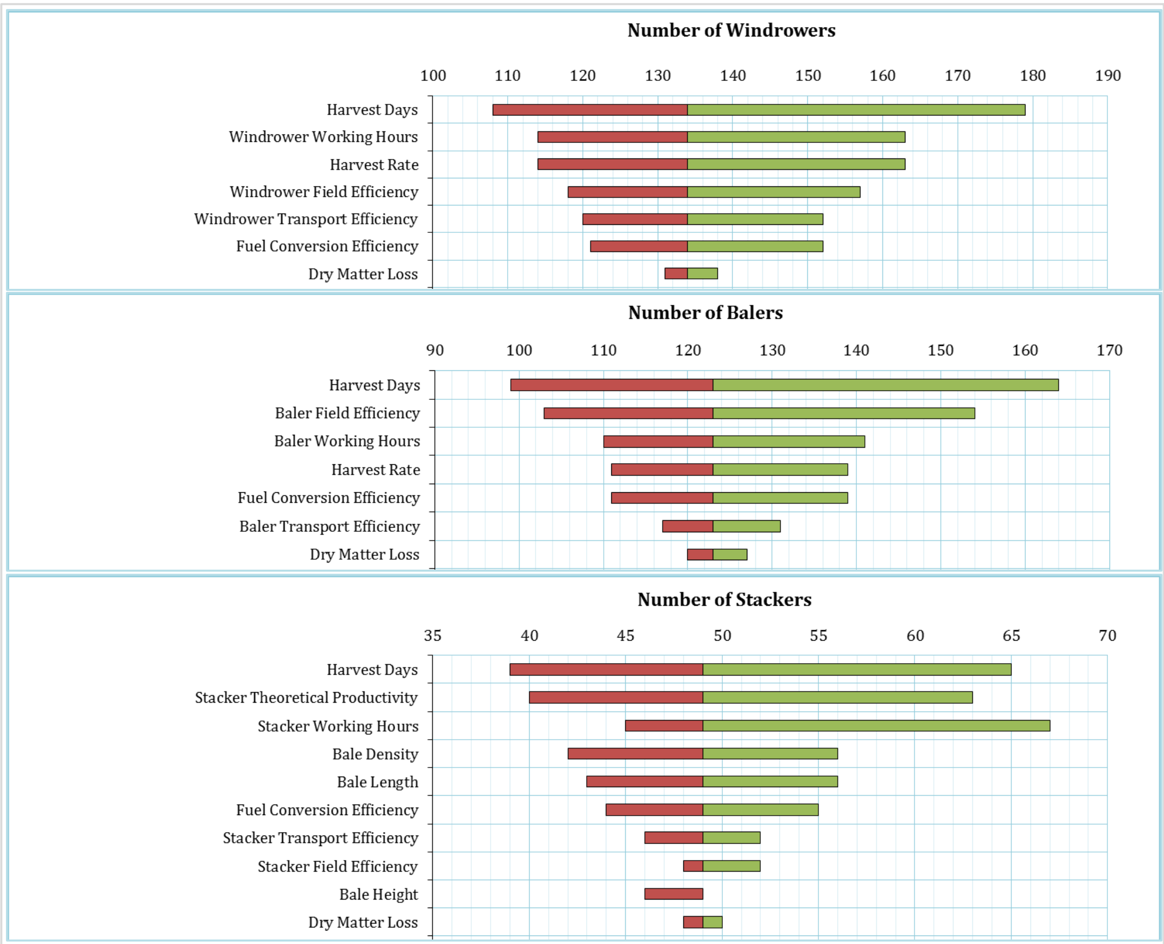

Figure 2.3: Sensitivities of annual windrowers, balers and stackers requirements for feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

For transportation activities at both the ends of the corn stover biomass supply chain, operating windows can be manipulated to some extent but remains close to those in Table 2.5. Average one-way travel distances for storage and biorefinery transports, respectively, are 15.7 (95% CR: 12.4-22.6) and 37.8 (95% CR: 29.7-54.2) km (i.e., 9.7 (95% CR: 7.6-13.0) and 23.3 (95% CR: 18.2-31.2) mi). One-way travel distance significantly impacts the quantities of loader and truck requirements for different transportation activities. Sensitivity analysis results (Figure 2.4) show that one-way travel distances for these operations are influenced by the number of satellite storage facilities (SSF), as the increase in number of SSF results in the decrease in their collection area resulting in reduction in the one-way travel distance for storage transport operation; however, this has reverse effect on the one-way travel distance for the biorefinery transport operation. With the increase in number of SSF, these are spread all over the overall collection area of the biorefinery, which results in the increase in one-way travel distances of trucks for this operation. In addition to the number of SSF, one-way travel distance is influenced by producer-specific characteristics in the region (i.e., agricultural production in Iowa, density of corn production and the producer's willingness to participate in harvesting stover for biorefinery purposes), harvest rate, fuel conversion efficiency and DML.

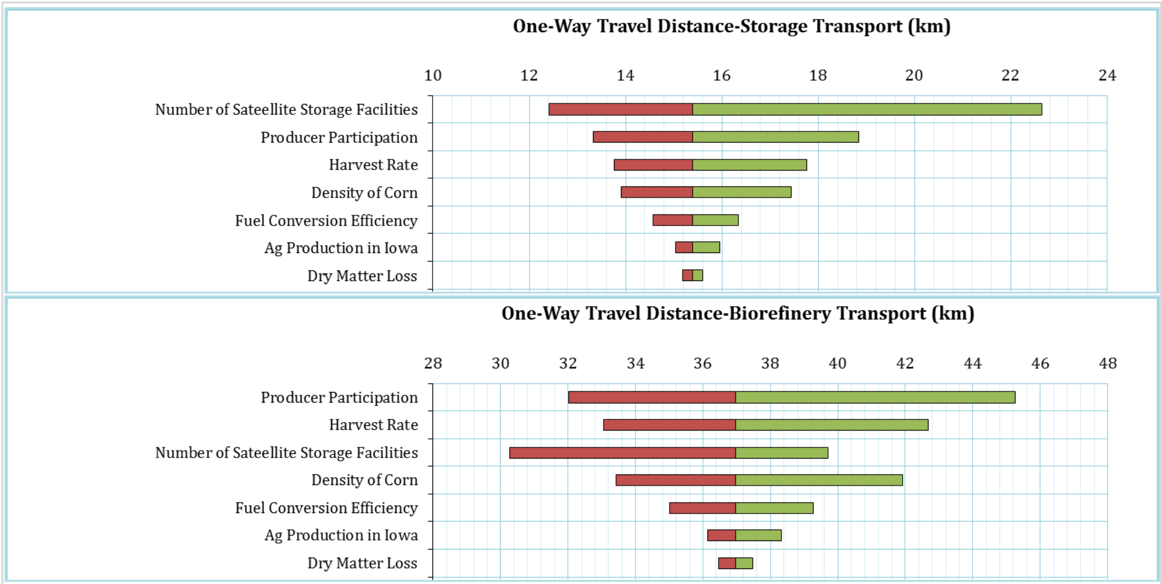

Figure 2.4: Sensitivities of one-way travel distances for storage and biorefinery transportation components of feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

Despite the travel distance of trucks in storage transport being shorter than that in biorefinery transport, annually more trucks are required for storage transport mainly because their operating window is narrower due to the need to transfer the bales from the field edge to the central storage facilities before the weather conditions worsen during winter. For biorefinery transport, the same number of stored bales are transported from the central storage facilities to the biorefinery plant but over the entire operating year. Storage transport is executed with larger number of teams each having fewer trucks due to the requirement to collect stover from the fields scattered all over the particular collection region and to move to the concentrated central storage facilities. For biorefinery transport, bales need to be moved from specific storage facilities to a biorefinery plant, so this operation is executed with fewer teams having higher number of trucks. Furthermore, transportation working durations (i.e., annual working days and daily working hours), physical properties of bale (i.e., density, length and height), fuel conversion efficiency, number of SSF, regional producer-specific characteristics (i.e., agricultural production in Iowa, density of corn production and producer's participation), harvest rate and DML influences the numbers of trucks and loaders for storage and biorefinery transports (Figure 2.5), and the variabilities associated with these parameters cause the wide 95% central range for annual trucks and loaders requirements (Table 2.5). Majority of these parameters can be optimized to reduce the overall quantities of trucks and loaders requirements for storage and biorefinery transports, and some of the potential strategies to achieve these targets are discussed in the later section of this paper.

Figure 2.5: Sensitivities of annual trucks and loaders requirements for storage and biorefinery transportation components of feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

Corn stover biomass supply chain for a 114 MLPY (30 MGPY) cellulosic biorefinery plant, on an average, requires around 250 thousand hours equivalent of labor each year (Figure 2.6). Around 60% of the average total labor requirement is for the transportation activities at two ends of the supply chain, and around 30% is for the stover bale harvest (i.e., combined windrowing and baling operations). Labor requirement is mainly dependent upon the farm machineries requirement for different processes of the supply chain. Labor requirement for the biomass storage operation is the least and, on an average, is around 3% of that for the overall supply chain. Based on the performances of different parameters of the supply chain, 95% central range on annual labor requirement of the supply chain falls between around 190 and 325 thousand hours. This spread is mainly governed by the fuel conversion efficiency by directly changing the overall biomass demand and supply requirements of the biorefinery, physical properties of bales (i.e., density, length and height) by directing changing the bale supply need of the biorefinery, machineries-specific characteristics (i.e., productivities and efficiencies) by directly changing their performances, and regional producer-specific characteristics (i.e., land in agricultural production, corn production density, producer participation and harvest rate) by directly changing the supply area for collecting corn stover biomass feedstock (Figure 2.7).

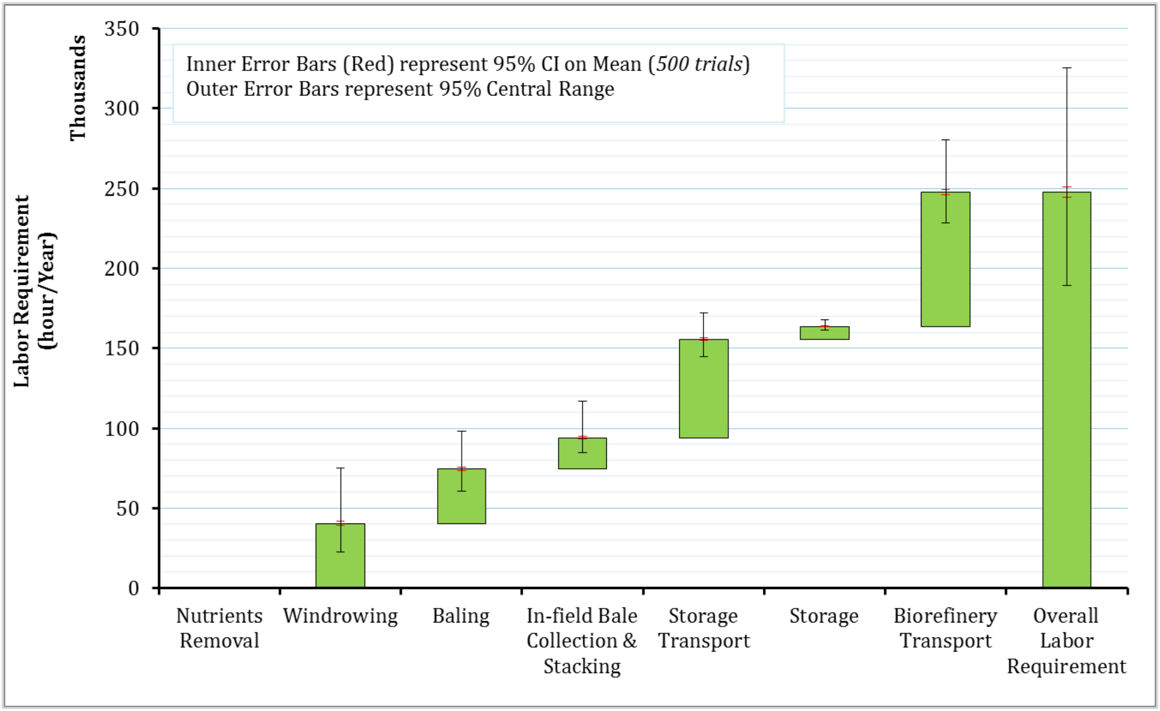

Figure 2.6: Annual labor requirements for the corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

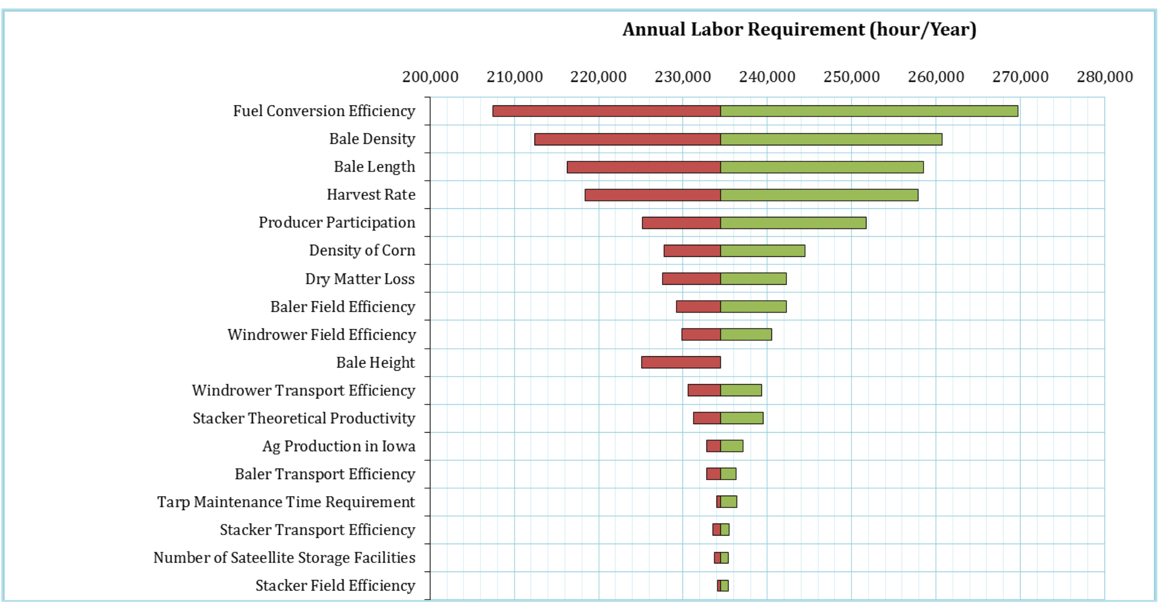

Figure 2.7: Sensitivity of annual labor requirement for feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

Annual fuel (diesel) consumption for the entire supply chain is, on an average, around 4.3 million (95% CR: 3.0-6.4 million) L (Figure 2.8) (i.e., 1.1 million (95% CR: 0.8-1.7 million) gal). For biorefinery gate delivered stover, overall fuel (diesel) consumption is, on an average, around 11.5 (95% CR: 7.9-17.3) L std. Mg^{-1} (Figure 2.9) (i.e., 2.8 (95% CR: 1.9-4.2) gal std. ton^{-1}). To put this into perspective, considering 0.9 \$-L^{-1} (3.5 \$-gal^{-1}) diesel price, in an optimistic working conditions (i.e., better performance of different supply chain parameters), cost of fuel consumed of biorefinery gate delivered stover can be reduced by around 3.3 \$-std. Mg^{-1} (3.0 \$-std. ton^{-1}) from the average cost, and under poor performance scenario, fuel cost share can increase by up to 5.4 \$-std. Mg^{-1} (4.9 \$-std. ton^{-1}), which creates a range of around 8.7 \$-std. Mg^{-1} (7.9 \$-std. ton^{-1}) of biorefinery gate delivered stover. Around 43% of the average fuel consumption for the supply chain is due to the two processes involved in stover harvest in multi-pass platform, i.e., windrowing and baling. Both of these operations contribute around 21.5% of the overall fuel consumption mainly due to the mechanical tasks involved in these processes. For baling, fuel is primary consumed to power the bale packaging mechanisms, whereas for windrowing, fuel is mainly consumed to power the chopper to shred stover lying on the field after grain harvest. Fuel consumption for the transportation activities at both the ends of the biomass supply chain is around 50% of the average overall fuel use, with that for biorefinery transport being higher than that for the storage transport mainly due to longer travel distances. In contrast to these activities fuel is not used for the storage operation as there are no machineries involved in this process.

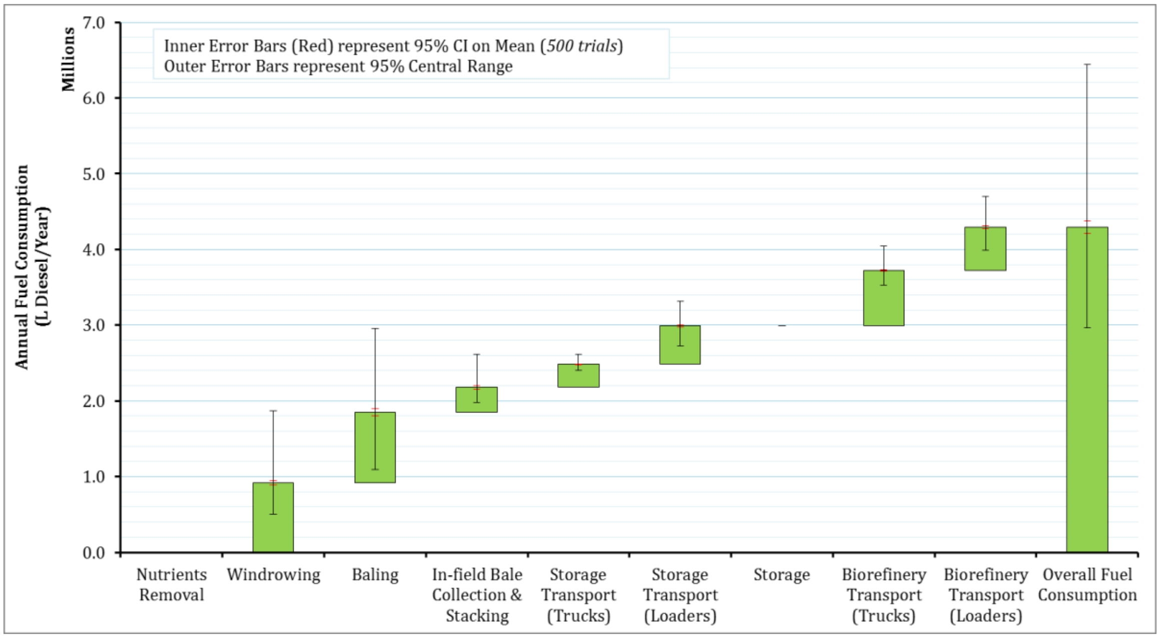

Figure 2.8: Annual fuel consumption for the operation of different farm machineries required for different processes of the corn stover biomass supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

The variability observed in fuel consumption is due to the variabilities in different supply chain parameters. Sensitivity analysis results (Figure 2.10) indicate that the annual fuel consumption is the most sensitive to fuel conversion efficiency as this reduces the overall stover demand of the biorefinery, and, thus, the overall fuel required for different operations of the supply chain. The other parameters that impact the overall supply chain fuel consumption include harvest rate, physical properties of bale (density, length and height), machineries-specific parameters (fuel consumptions, productivities and efficiencies), producer-specific characteristics (land in agricultural production, corn production density and producers participation). Relative influences of these parameters are included in Figure 2.10, and strategic improvements in these parameters can significantly reduce the overall fuel use of the supply chain.

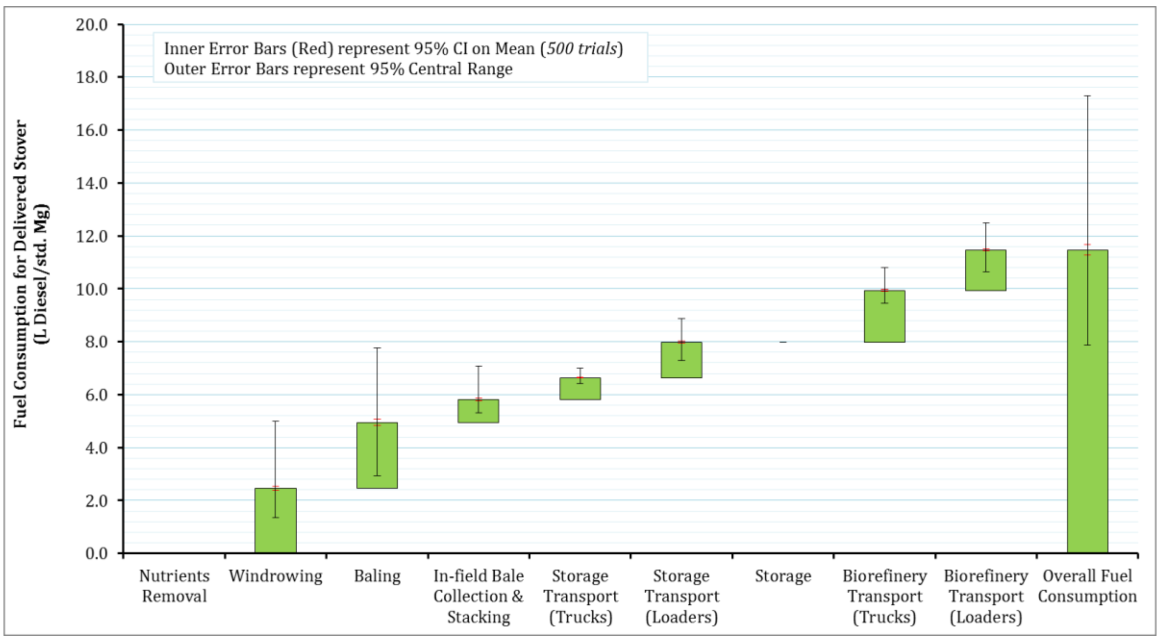

Figure 2.9: Fuel consumption for the operation of different farm machineries required for different processes of the corn stover biomass supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant to deliver 1 std. Mg of corn stover to the biorefinery gate

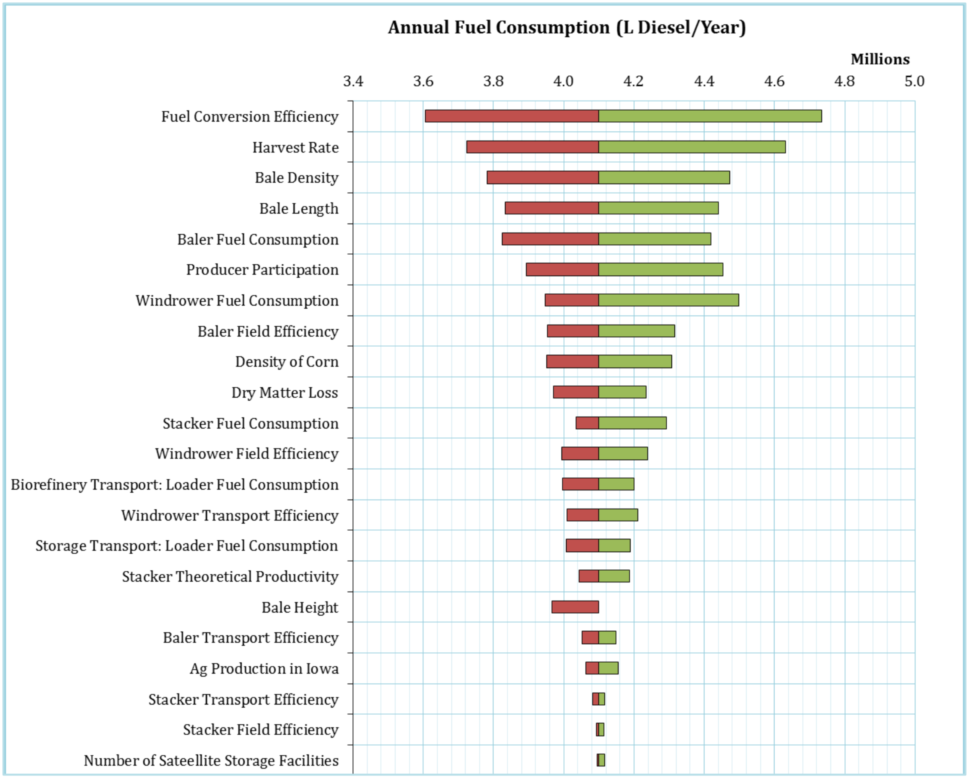

Figure 2.10: Sensitivity of annual fuel consumption for feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

2.4.3 Cost of corn stover biomass feedstock supply chain

Average cost of biorefinery gate delivered corn stover biomass feedstock is estimated to be 121.9 (95% CI on mean: 120.7-123.2; 95% CR: 98.9-152.3) \$-std. Mg^{-1} (i.e., 110.6 (95% CI on mean: 109.5-111.8; 95% CR: 89.7-138.2) \$-std. ton^{-1}). The uncertainties in these costs (as expressed in terms of 95% central range) are due to the variabilities in different supply chain parameters. The parameters impacting the overall cost have been identified using sensitivity analysis methodology, and are thoroughly discussed in the next section. The average costs of biorefinery gate delivered stover and its different components are included in Figure 2.11. Furthermore, constituents of different supply chain cost components are included in the supporting material (Supporting Material, Figures S2.3-S2.9), and are briefly discussed in this section. On an average, transportation activities at both the ends of the supply chain, and the two processes involved in harvesting corn stover bales (i.e., windrowing and baling) each comprises around 30% of the overall supply chain cost of biorefinery gate delivered stover. Average cost share of biorefinery transport is higher than that of storage transport by around 2% points; and, the average cost share of baling operation is almost twice that of the windrowing operation. Average nutrients replacement cost comprises around 21% of the overall cost, and the stacking and administrative activities each contributes slightly less than 10% of the overall cost. Storage is the least cost intensive process with only around 3% share on the overall cost.

Average cost to replenish nutrients (N, P and K) removed from the field during stover harvest is around 26 (95% CR: 15-38) \$-std. Mg^{-1} (i.e., 24 (95% CR: 13-35) \$-std. ton^{-1}), around half of which is due to the need to replenish potassium fertilizer (Supporting Material, Figure S2.3). Costs for replenishing nitrogen fertilizer is the next significant component of this cost and covers around 38% of the overall cost (Supporting Material, Figure S2.3). The conflicting views in scientific community regarding the need to replenish nitrogen removed with stover harvest have been discussed earlier in this paper. This analysis quantifies the cost associated with nitrogen replenishing so that the readers could use the results as per their need and arguments. Excluding cost for replenishing nitrogen from this analysis reduces the average nutrients replenishing and overall supply chain costs, respectively, to around 16 and 112 \$-std. Mg^{-1} (i.e., 14.5 and 101.5 \$-std. ton^{-1}). Furthermore, disintegrating the nutrients replenishing from the overall supply chain yields the average cost of 95.8 \$-std. Mg^{-1} (i.e., 86.9 \$-std. ton^{-1}), which is the cost of the different physical operations of the supply chain. Further analysis reveals that the harvesting (i.e., combined windrowing and baling operations) and transportation (i.e., combined storage and biorefinery transports) each share around 38% of this cost, stacking and administrative costs each share around 10%, and storage shares around 4%. These results suggest that the costs of bale harvesting and transportation activities share the significant portion of the overall supply chain cost and need further work for their performances optimization. Some potential strategies to reduce the cost of these operations are thoroughly discussed in a later section.

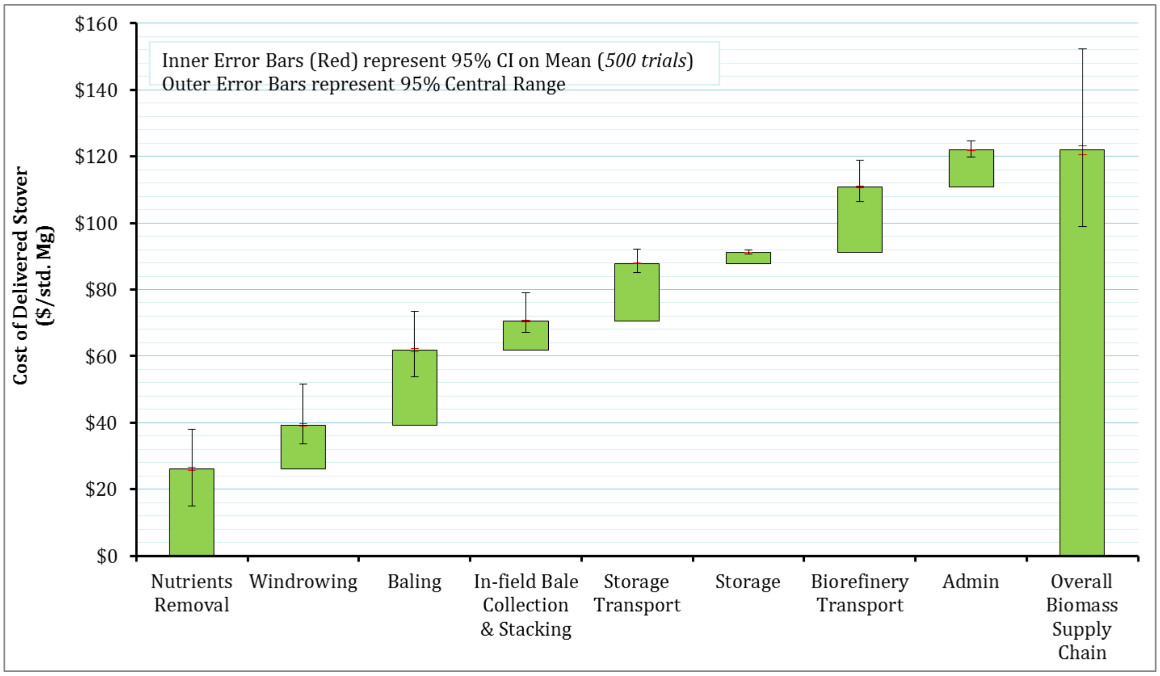

Figure 2.11: Cost of biorefinery gate delivered stover for a 114 MLPY (30 MGPY) plant

Average costs of windrowing, baling and stacking operations (Supporting Material, Figures S2.4-S2.6) are, respectively, 13.2 (95% CR: 7.5-25.5), 22.4 (95% CR: 14.6-34.2) and 8.8 (95% CR: 5.5-17.3) $-std. Mg^{-1} (i.e., 12.0 (95% CR: 6.8-23.1), 20.3 (95% CR: 13.2-31.0) and 8.0 (95% CR: 5.0-15.7) $-std. ton^{-1}). For all these three operations, costs related to equipment (i.e., capital recovery and tractor rental costs) share around 45% of the overall cost. Thus, reduction in the quantities of farm machineries required for different operations can significantly reduce this cost. In addition to the equipment related costs, other costs for these operations (i.e., energy, labor, repair and maintenance, and administrative costs) are almost balanced and are in the range around 10-15% of the overall cost. Average biomass storage cost (Supporting Material, Figure S2.8) is 3.4 (95% CR: 2.9-4.1) \$-std. Mg^{-1} (i.e., 3.1 (95% CR: 2.6-3.7) \$-std. ton^{-1}), and the cost of tarp alone constitutes around half of this cost. Costs of rock, land, labor and administrative tasks are almost balanced and are in the range around 10-15% of the overall storage cost. The overall costs of storage and biorefinery transports (Supporting Material, Figures S2.7 and S2.9), respectively, are 17.3 (95% CR: 14.5-21.5) and 19.6 (95% CR: 15.2-27.5) \$-std. Mg^{-1} (i.e., 15.7 (95% CR: 13.1-19.5) and 17.8 (95% CR: 13.8-25.0) \$-std. ton^{-1}). Cost of biorefinery transport is higher than that of storage transport mainly due to longer travel distance. For both the storage and biorefinery transports, combined cost of renting trucks and loaders is around 80% of their overall cost. Furthermore 60% of the overall transportation costs are for truck rental alone, which includes their operator and fuel costs. Thus, increasing the payload capacities of trucks and reducing their quantities can be the key to reducing the overall supply chain cost. Payload capacities of trucks can be increased by enhancing bulk densities of feedstock.

In addition to the cost of a Mg of biorefinery gate delivered stover (discussed so far), annual working capital and the cost of biorefinery gate delivered stover to produce a liter of cellulosic ethanol are important, as the former provide the information on the annual budgetary requirement for the supply chain and the later provides the mean to compare the cost of delivering stover to the biorefinery gate against the target cellulosic ethanol producing cost. Annual working capital for the corn stover biomass supply chain for a 114 MLPY (30 MPGY) biorefinery is around \$45.6 million (95% CR: \$36.6-58.7 million) (Supporting Material, Figure S2.1). Pre-information on the tentative annual working capital requirement can help the biorefineries manage supply chain efficiently. Average cost of biorefinery gate delivered stover to produce a unit volume of cellulosic ethanol (Supporting Material, Figure S2.2) is 0.40 (95% CR: 0.32-0.52) \$-L^{-1} (i.e., 1.51 (95% CR: 1.21-1.97) \$-gal^{-1}). To put this into perspective, for cellulosic ethanol to be economically competitive with gasoline (comparing in energy content basis), considering recent three years (2010-2012) average gasoline retail price of 0.87 \$-L^{-1} (i.e., 3.3 \$-gal^{-1}) in Midwest (EIA, 2013), cost of ethanol need to be 0.58 \$-L^{-1} (i.e., 2.2 \$-gal^{-1}). Thus, the average feedstock supply chain cost of 0.40 \$-L^{-1} (i.e., 1.5 \$-gal^{-1}) will be around 68% of this ethanol price, which reflects the need for further research in this area to improve the performances of different parameters. Even with excluding the nutrients replenishment cost from this analysis, average cost of biorefinery gate delivered stover to produce a unit volume of cellulosic ethanol is 0.32 \$-L^{-1} (i.e., 1.2 \$-gal^{-1}), which is around 55% of the ethanol price to be competitive with gasoline. As discussed earlier, costs of transportation at both the ends of the supply chain and that of harvesting including windrowing and baling operations constitute the major fraction of the overall supply chain cost, thus, efforts need to be directed toward optimizing the performances of these processes and minimizing their costs. Some of the potential strategies to do so are discussed later in this paper.

2.4.4 Sensitivity analysis of the cost of biorefinery gate delivered stover

Ranges to which the cost of a std. Mg of biorefinery gate delivered stover varies depending upon the pessimistic, most likely and optimistic values of 50 different parameters (Table 2.3) and their rankings based on their relative influence on this cost are presented in Figure 2.12. The most likely cost of biorefinery gate delivered stover (estimated deterministically using the most likely values for different supply chain parameters, and should not be confused with previously discussed cost generated stochastically using Monte-Carlo simulation method) is 117.0 \$-std. Mg^{-1} (i.e., 106.1 \$-std. ton^{-1}). This cost is identified to be the most sensitive to bale density, followed by harvest rate, bale length and baler field efficiency, all of which are related to the baling operation. Reduction in bale density from 166.8 to 144.2 std. kg m^{-3} (i.e., 10.4 to 9 std. lb ft^{-3}) can increase the overall supply chain cost by 8.8 \$-std. Mg^{-1} (8 \$-std. ton^{-1}), and an increase to 192.2 std. kg m^{-3} (i.e., 12 std. lb ft^{-3}) can reduce the overall cost by 7.7 \$-std. Mg^{-1} (7 \$-std. ton^{-1}). Likewise changes in harvest rate, bale length and baler field efficiency from the most likely values to the pessimistic values can increase the overall supply chain cost by 8.1, 7.3 and 4.5 \$-std. Mg^{-1} (i.e., 7.4, 6.7 and 4.1 \$-std. ton^{-1}), respectively, and changes to the optimistic values can decrease this cost by 5.7, 5.7 amd 3.2 \$-std. Mg^{-1} (i.e., 5.2, 5.2 and 2.9 \$-std. ton^{-1}), respectively. Thus, in the pessimistic and optimistic operating conditions, the combined effect of these 4 parameters can, respectively, increase the most likely overall supply chain cost by 28.7 \$-std. Mg^{-1} (26.1 \$-std. ton^{-1}) and decrease by 22.3 \$-std. Mg^{-1} (20.2 \$-std. ton^{-1}), thus, the range of the overall cost can be from 94.7 to 145.7 \$-std. Mg^{-1} (85.9 to 132.2 \$-std. ton^{-1}). Likewise, the combined effect of pessimistic and optimistic operating conditions of all the parameters used for sensitivity analysis can change the range of overall cost to 52.9-201.9 \$-std. Mg^{-1} (47.9-183.2 \$-std. ton^{-1}). Thus, improvements in the corn stover biomass supply chain parameters to the extent included in Table 2.3 can reduce the overall cost of biorefinery gate delivered stover by more than half.

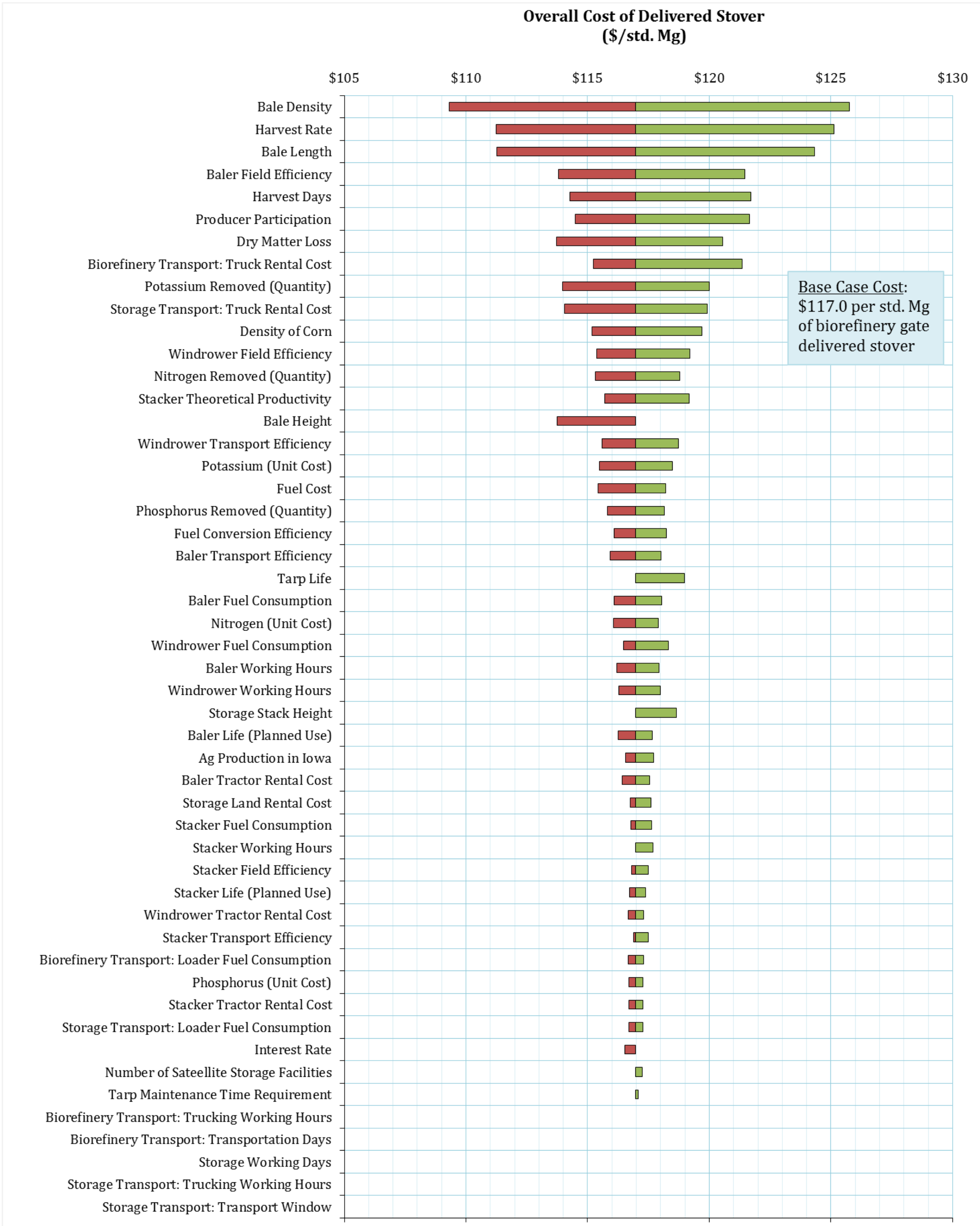

Figure 2.12: Sensitivity of the cost of delivering stover to the gate of a 114 MLPY (30 MGPY) biorefinery plant on the pessimistic, most likely and optimistic values of 50 different supply chain system parameters (Table 2.3)

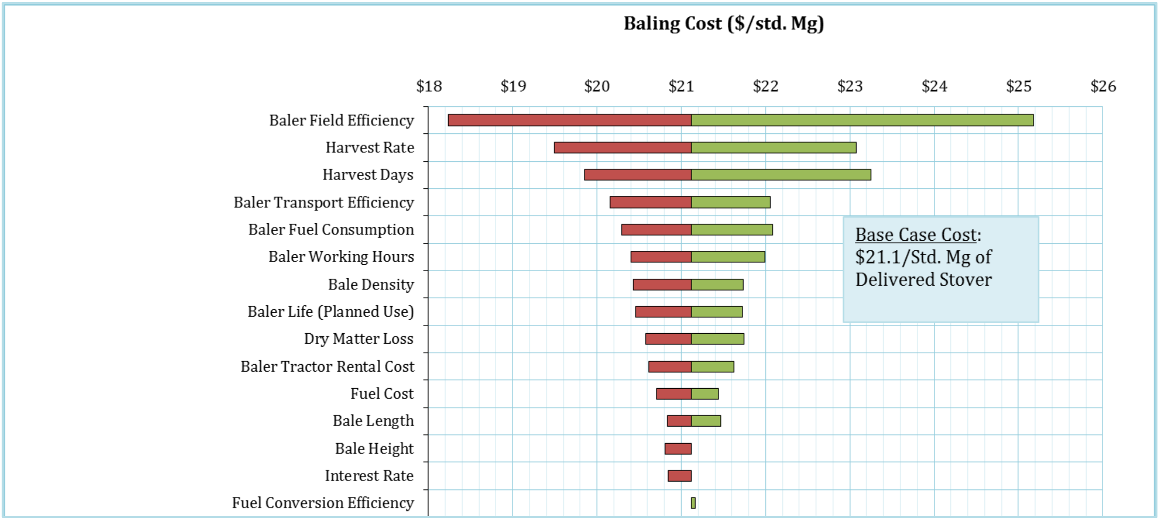

Figure 2.13: Sensitivity of baling cost for supplying feedstock to the gate of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

Bale density has been identified to be the most sensitive supply chain parameter and is attained during the baling process; however, sensitivity analysis on the baling operation (Figure 2.13) shows that the range of bale density considered in this analysis changes the overall baling cost only by 1.3 $\$$-std. Mg^{-1} (1.2 $\$$-std. ton^{-1}), but changes the overall supply chain cost by 16.4 $\$$-std. Mg^{-1} (14.9 $\$$-std. ton^{-1}). Thus, bale density has the global impact on the supply chain rather than only locally influencing the baling cost. This is mainly due to the reason that bale density influences the costs of all other supply chain components succeeding baling operation (Supporting Material, Figure S2.12-S2.16). Bale density range used in this analysis influences stacking, storage transportation, storage, biorefinery transportation, and administrative costs by 2.3, 4.9, 1.0, 5.5 and 1.5 $\$$-std. Mg^{-1} (2.1, 4.5, 0.9, 5.0 and 1.4 $\$$-std. ton^{-1}), respectively, and is ranked as the top 3 most sensitive supply chain parameters impacting the overall costs of these processes (Supporting Material, Figure S2.12-S2.16). Likewise, bale length and harvest rate have global impacts on the supply chain cost as these influence the costs of different components of the supply chain (Figures 2.12, 2.13 and (Supporting Material, Figure S2.11-S2.16)). Bale density and length reduce stacking, storage transportation and biorefinery transportation costs by reducing the quantities of bale units to be handled and transported, and that of storage by reducing the land area requirement. Harvest rate reduces the cost mainly by reducing the feedstock supply area. Furthermore, these reduce the administrative cost associated with these operations. Unlike these parameters, baler field efficiency influences only baling and associated administrative costs, and, thus, has local impact on the baling operation (Figures 2.12 and 2.13). Regardless of having local or global impacts, all of these parameters (except harvest rate) can be improved only during the baling process. Decision on harvest rate depends on the landscape type and the optimal quantity of stover permitted to be sustainably removed from the field, and the configurations of field harvesting machineries (i.e., windrowers and balers). It should also be noted that all results are represented in terms of std. Mg (i.e., 0% moisture and 8% ash contents) to eliminate bias due to moisture and ash contents; however, overall feedstock cost varies with moisture and ash contents if results are represented in terms of their true moisture and ash contents.

2.5 Potential strategies to reduce corn stover biomass supply chain cost and achievable targets

This study, under the most likely scenario (using the 'most likely' values of parameters in Table 2.3), estimates the cost of supplying corn stover biomass feedstock to the biorefinery gate in bale format including the costs associated with replenishing nutrients removed from the field during stover collection to be 117.0 \$-std. Mg^{-1} (i.e., 106.1 \$-std. ton^{-1}). The costs discussed in this section should not be confused with the supply chain costs discussed in the previous sections. Those were stochastically generated as the outcome of Monte-Carlo analysis providing cost distributions for different processes using distributions of input parameters included in Table 2.1; however, the costs discussed in this section are deterministic estimates as a single value outcome using data in Table 2.3. There are conflicting views regarding the need to replenish nitrogen removed from field during stover harvest, as discussed earlier in this paper, and the choice depends upon different farming practices (rotations and tillage), use of cover crops, etc. In contrast to this, the need to replenish phosphorus and potassium fertilizer has been widely accepted. Furthermore, methods to optimize the fertilizers use for crop farming are more related to the crop production phase, and, thus are out of the scope of this work. Thus, the potential strategies to reduce the overall supply chain cost discussed in the following texts will focus on the other components than the nutrients. This point forward, overall cost of supply chain refers to the overall supply chain cost excluding nutrients replacement cost. The most likely overall supply chain cost is 90.8 \$-std. Mg^{-1} (i.e., 82.4 \$-std. ton^{-1}). In earlier sections, parameters influencing the feedstock supply, resources requirements and the overall costs of the supply chain were identified and briefly discussed. In the following texts, three potential strategies to reduce the overall supply chain cost by optimizing the major supply chain parameters are identified and discussed and the impacts of the achievable values of different supply chain parameters on the overall cost reduction are tabulated in Table 2.6.

Table 2.6: Summary of potential reductions in the overall cost of corn stover biomass supply chain depending upon the strategic improvements in some major supply chain parameters

Parameters	*Units	*Values of		Overall Supply Chain	Windrowing	Baling	Stacking	Storage Transport	Storage	Biorefinery Transport	Admin	*Achieved Overall Supply Chain Costs
		Most Likely	Target									
Baseline Cost	\$-std. Mg^{-1} (\$-std. ton^{-1})	All	-	90.8 (82.4)	11.9 (10.8)	21.1 (19.2)	7.8 (7.1)	17.0 (15.4)	3.4 (3.1)	19.0 (17.2)	10.6 (9.6)	90.8 (82.4)
Overall Cost Savings	\$-std. Mg^{-1} (\$-std. ton^{-1})	-	All	39.0 (35.4)	6.3 (5.7)	9.3 (8.4)	3.1 (2.8)	6.7 (6.1)	0.7 (0.7)	9.3 (8.4)	3.6 (3.3)	
Final Cost	\$-std. Mg^{-1} (\$-std. ton^{-1})	-	All	51.9 (47.1)	5.7 (5.1)	11.9 (10.8)	4.7 (4.3)	10.3 (9.3)	2.6 (2.4)	9.7 (8.8)	7.0 (6.4)	51.9 (47.1)
Parameter-wise Breakdown for Overall Cost Savings				*Cost Savings for Corn Stover Biomass Feedstock Supply Chain and its Components excluding								
Producers' Participation	%	30%	40%	2.5 (2.3)	-	-	-	0.6 (0.6)	-	1.6 (1.5)	0.2 (0.2)	88.3 (80.1)
Harvest Rate	std. Mg ha^{-1} (std. ton ac^{-1})	3.6 (1.6)	4.5 (2.0)	5.7 (5.2)	1.8 (1.6)	1.6 (1.5)	-	0.5 (0.5)	-	1.3 (1.2)	0.5 (0.5)	82.6 (74.9)
Dry Matter Loss (DML)	%	7.5%	5.0%	2.6 (2.3)	0.3 (0.3)	0.5 (0.5)	0.2 (0.2)	0.5 (0.5)	0.1 (0.1)	0.7 (0.6)	0.3 (0.3)	80.0 (72.6)
Bale Density	std. kg m^{-3} (std. lb ft^{-3})	166.8 (10.4)	192.2 (12.0)	7.7 (7.0)	-	0.7 (0.6)	1.1 (1.0)	2.3 (2.0)	0.4 (0.4)	2.5 (2.3)	0.7 (0.6)	72.4 (65.6)
Bale Length	cm (in)	243.8 (96.0)	274.3 (108.0)	5.7 (5.2)	-	0.3 (0.3)	0.9 (0.8)	1.9 (1.7)	-	2.1 (1.9)	0.5 (0.5)	66.6 (60.4)
Bale Height	cm (in)	86.4 (34.0)	91.4 (36.0)	3.2 (2.9)	-	0.3 (0.3)	0.5 (0.4)	0.9 (0.9)	0.2 (0.2)	1.1 (1.0)	0.3 (0.3)	63.4 (57.5)
Windrower Field Efficiency	%	70.0%	80.0%	1.6 (1.5)	1.5 (1.3)	-	-	-	-	-	0.1 (0.1)	61.8 (56.0)
Windrower Transport Efficiency	%	85.0%	95.0%	1.4 (1.2)	1.3 (1.1)	-	-	-	-	-	0.1 (0.1)	60.4 (54.8)
Baler Field Efficiency	%	50.0%	60.0%	3.2 (2.9)	-	2.9 (2.6)	-	-	-	-	0.3 (0.3)	57.2 (51.9)
Baler Transport Efficiency	%	90.0%	95.0%	1.1 (1.0)	-	1.0 (0.9)	-	-	-	-	0.1 (0.1)	56.2 (51.0)
Stacker Transport Efficiency	%	90.0%	95.0%	0.1 (0.1)	-	-	0.1 (0.1)	-	-	-	0.0 (0.0)	56.1 (50.9)
Harvest Days	days yr^{-1}	32.0	40.0	2.7 (2.5)	0.8 (0.7)	1.3 (1.2)	0.4 (0.3)	-	-	-	0.2 (0.2)	53.3 (48.4)
Windrower Working Hours	hr day^{-1}	8.5	10.0	0.7 (0.6)	0.6 (0.6)	-	-	-	-	-	0.1 (0.1)	52.7 (47.8)
Baler Working Hours	hr day-1	8.0	9.0	0.8 (0.7)	-	0.7 (0.6)	-	-	-	-	0.1 (0.1)	51.9 (47.1)

* Units and values in parentheses are in U.S. customary units

Reducing stover collection area for supplying feedstock to the biorefinery plant:

The overall stover feedstock collection area can be practically reduced either by increasing the producers' participation in stover harvest for cellulosic biorefineries or by increasing the harvest rate of the stover from the field or directly by reducing the biomass supply requirement of the biorefinery by decreasing the overall DML of the supply chain or increasing the fuel conversion efficiency. Among these, fuel conversion efficiency is directly related to the ethanol production phase of the biorefinery, and is out of scope of this work. Thus, the impacts of fuel conversion efficiency on the overall supply chain cost and the methods for its optimization have not been discussed here.

Producer's participation reduces the stover supply area requirements by directly increasing the densities of corn fields nearby biorefinery location. Producers' participation in stover harvest for cellulosic biorefineries can be increased by educating farmers in one's state on the many potential social, economic and agronomic benefits brought about by this industry in the region. Advent of cellulosic biorefineries in one's state can uplift the social as well as economic standards of the residents by creating employment and raising their living standards. At the same time, there are studies which suggest that collecting stover from the field in continuous corn increases soil temperature resulting in an increased rate of vegetative development after planting (Mann et al., 2002). Additionally, Coulter and Nafziger (2008) have suggested that higher amount of corn residue is a source of inoculums for many corn diseases, and the placement of corn shoot residues near corn seeds delays seedling development during planting. With proper education of farmers, producers' participation in stover collection can, potentially, be increased from the currently assumed baseline scenario of 30 to 40%. This can reduce the overall supply chain cost by around 2.5 \$-std. Mg^{-1} (i.e., 2.3 \$-std. ton^{-1}), primarily by reducing the overall supply area, which, consequently, impacts the transportation activities at the two ends of the supply chain and the associated administrative costs (Table 2.6) by reducing the travel distances between field, satellite storage locations and the biorefinery plant.

The overall supply area for stover collection can also be reduced by increasing the harvest rate, which involves removing more stover per unit land area. Proper education on the multifarious benefits of stover collection from the field, backed up with scientific findings, can convince farmers increase the harvest rate of corn stover from their fields to some extent in addition to increasing their participation as discussed earlier. Then, attaining increased harvest rate needs innovation in current machineries design for increasing the intake of biomass in the windrowers and the balers, as well as allowing variable rate harvesting. Additionally, the removal of more stover can be sufficed by with the use of cover crops to provide additional ground cover, minimize erosion, maintain soil climate and minimize soil contamination. Innovations in windrower and baler design combined with implementing these practices, harvest rate can be sustainably increased from current level of 3.6 std. Mg ha^{-1} (1.6 std. ton ac^{-1}) to 4.5 std. Mg ha^{-1} (2.0 std. ton ac^{-1}). This can save an additional 5.7 \$-std. Mg^{-1} (i.e., 5.2 \$-std. ton^{-1}), primarily by reducing the overall supply area for corn stover feedstock resulting in reduced travel distance for trucks and improving the productivities of windrowers and balers (Table 2.6). Thus, increase in harvest rate can significantly reduce the harvesting and transportation costs. In addition to increasing producers' participation and harvest rate, corn stover supply area requirements can be reduced by decreasing the overall quantity of stover that need to be harvested. This can be achieved by reducing the DML occurring in different processes of the supply chain. Production-scale data obtained from the field studies conducted at Iowa State University indicate that the proper storage of biomass with tarp cover can limit the DML to less than 3%. Thus, considering DML for the supply chain to reduce from 7.5% to 5%, which is practically feasible with best management practices, the overall supply chain cost can reduce by an additional 2.6 \$-std. Mg^{-1} (i.e., 2.3 \$-std. ton^{-1}), and the cost saving is observed in all the components of the supply chain, as reduction in DML reduces the actual biomass quantity passing through different processes. Thus, optimizing these three supply chain parameters for reducing the overall feedstock supply area requirements of the biorefinery can reduce the overall supply chain cost by 10.8 \$-std. Mg^{-1} (i.e., 9.8 \$-std. ton^{-1}).

Reducing corn stover bale supply quantity delivered to the biorefinery gate:

For same amount of corn stover, overall bale supply requirement of a biorefinery can be significantly reduced by improving bale density, and increasing its length and height. Reduction in the overall bale supply requirement has impact on all the post-baling operations of the supply chain, as stover is delivered in the form of bale, and with reduction in its quantity, the unit handling requirements are reduced. Bale density can be improved by innovative baler design capable of applying greater pressure over the extended duration, selecting twine that can restrain bale rebounding and better operator trainings. With these technological and operational improvements, there is sufficient potential to improve bale density from current baseline value of 167 std. kg m^{-3} (10.4 std. lb ft^{-3}) to 192 std. kg m^{-3} (12 std. lb ft^{-3}). With this improvement in bale density, the overall supply chain cost can reduce by an additional 7.7 \$-std. Mg^{-1} (i.e., 7.0 \$-std. ton^{-1}), which also makes it the single largest cost driver among different major supply chain parameters (Table 2.6).

The overall bale supply requirement can be further reduced by increasing the lengths and heights of the bales. Currently, 244 cm (96-in) long bales are common; however, the bale length is controllable by the operator, so this can be simply increased to 274 cm (108-in) by the operators. The major impediment in implementing these in current supply chain would be the selection of the handling equipment for extended bales, which is not impossible. Equipment capable of handling these longer bales can be custom manufactured, and will be common upon widespread use of longer bales. In addition to the bale length, bale height is the other major supply chain parameter that can reduce the overall bale quantities required by the supply chain. Production-scale data show that the height of bale is usually 86 cm (34-in) although popular as 91 cm (36-in) bales. 91 cm bales can be generated with innovation in baling chamber by increasing its height, as well as with operator training. These improvements in bale length and height can potentially reduce the overall supply chain cost, respectively, by additional 5.7 and 3.2 \$-std. Mg^{-1} (i.e., 5.2 and 2.9 \$-std. ton^{-1}) (Table 2.6). Thus, optimizing bale density, length and height for reducing the overall bale supply requirement of the biorefinery can reduce the overall supply chain cost by an additional 16.6 \$-std. Mg^{-1} (i.e., 15.1 \$-std. ton^{-1}).

Reducing the quantities of in-field farm machineries:

Quantities of in-field farm machineries (i.e., windrower, baler and stacker) can be reduced by improving their productivities and increasing the working durations for different field operations. Improving productivities can reduce the overall time requirement, and extended operation durations can allow extra time for different operations. In both situations, overall quantities of machineries required can be significantly reduced. Unlike other parameters (like bale density, length, harvest rate, DML, etc.) which influenced more than one operation of the supply chain, both of these parameters impact only their respective operations and associated machineries. Productivities of these machineries usually are the functions of harvest rate (for windrower and baler, expressions 2.1 and 2.2) and efficiencies. Impact of harvest rate has already been discussed under one of the former strategies for cost reduction. Efficiencies of in-field farm machineries are categorized as field and transport efficiency. Field efficiency provides the indication of the actual amount of time these equipment are operational during the operating hours, and transport efficiency provides information on the time spent for moving these machineries from one field to the other. Improvements in efficiencies can improve the overall productivities of these machineries, and, consequently reduce the overall cost of the supply chain by decreasing their quantities, fuel and labor requirements. These efficiencies can be improved with advanced operator training and real-time feedback tools that can improve the operating logistics and coordination of in-field equipment. With best management practices and enhanced operator skills, field efficiencies of windrowers and balers, and transport efficiencies of windrowers, balers and stackers can potentially be increased from their current baseline values of 70, 50, 85, 90 and 90% to 80, 60, 95, 95 and 95%, respectively. These enhanced efficiencies can reduced the overall supply cost by an additional 7.3 \$-std. Mg^{-1} (i.e., 6.7 \$-std. ton^{-1}) (Table 2.6).

Operating windows for different in-field operations usually depend upon the weather conditions; however, in seasons with better weather conditions current harvest window of 32 days-yr^{-1} can be extended to 40 days-yr^{-1}, which can significantly reduce the overall equipment requirements for different operations, resulting in the reduction in the overall supply chain cost. In addition to the harvest window, daily working durations for different field operations can be extended with good management practices focused on utilizing more daylight hours. With this, it is likely that windrowing and baling daily working hours can be increased from 8.5 and 8 hr day^{-1} to 10 and 9 hr day^{-1}. With these extended working durations, the overall supply chain cost can further be reduced by an additional 4.2 \$-std. Mg^{-1} (i.e., 3.8 \$-std. ton^{-1}) (Table 2.6). Thus, combined efficiency improvement and extended working durations can reduce the overall supply chain cost by an additional 11.5 \$-std. Mg^{-1} (i.e., 10.5 \$-std. ton^{-1}).

Implication of stover supply chain cost reduction on federal mandate for biofuels productions:

Strategic improvement of the major supply chain parameters can result in a 39 \$-std. Mg^{-1} (i.e., 35.4 \$-std. ton^{-1}) reduction in the overall supply chain cost, bringing it down to 51.9 \$-std. Mg^{-1} (i.e., 47.1 \$-std. ton^{-1}) from the current baseline cost of 90.8 \$-std. Mg^{-1} (i.e., 82.4 \$-std. ton^{-1}). Majority of this saving comes from the two processes involved in multi-pass harvesting (i.e., windrowing and baling) and the transportation activities at two ends of the supply chain. Costs of each harvesting and transportation activities can be reduced by around 15 \$-std. Mg^{-1} (i.e., 14 \$-std. ton^{-1}). Combined impacts of these achievable corn stover supply chain cost reduction strategies can reduce the baseline cost of the quantity of stover delivered to the biorefinery gate, excluding nutrients, to produce unit volume of ethanol from 0.30 \$-L^{-1} (1.13 \$-gal^{-1}) to 0.17 \$-L^{-1} (0.65 \$-gal^{-1}). As discussed earlier, for cellulosic ethanol to be economically competitive with gasoline, its overall cost need to be 0.58 \$-L^{-1} (i.e., 2.2 \$-gal^{-1}). Thus, the share of the average supply chain cost on the overall cellulosic ethanol production cost to compete economically with gasoline reduces from around 50% to around 30%.

This further highlights the significance of the impacts created by these achievable cost optimization strategies on the success of the overall second generation biofuels industries.

2.6 Conclusions

Corn stover biomass will be the primary feedstock choice for the first-generation cellulosic biorefineries in the Midwestern United States. Thus, for uninterrupted operation of these plants, year-round supply of corn stover needs to be secured, which will require a robust, efficient and cost-effective feedstock supply chain. This analysis considers corn stover biomass feedstock supply chain of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery plant. Different components of this supply chain include corn stover harvesting (windrowing and baling), in-field bales collection and stacking at the field-edge, handling and transportation of bales from the field-edge to the distributed central storage facilities and, then, to the biorefinery plant, storage, and finally the audit of nutrients removed during stover collection from the field. For analyzing the techno-economics of such feedstock supply chain, a macro-enabled spreadsheet-based model is developed, and the inputs are mainly populated with data collected through production-scale field tests conducted in Iowa. Major outcomes from this model include the estimates on resources requirements (i.e., labor, machineries, consumables, land, etc.), fuel requirements for the operation of different machineries, and the cost of biorefinery gate delivered stover.

A Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery plant, on an average, requires around 0.95 million corn stover bales supply, 250 thousand hours equivalent of labor and 4.3 million L (1.2 million gal) of diesel fuel each year. Around 60% of the total labor requirement and 50% of the overall fuel use are for the transportation activities at the two ends of the supply chain. The second most labor and energy intensive process is harvesting (combined windrowing and baling operations). Harvesting shares around 30% of the overall labor requirements and 40% of the overall fuel use for the entire supply chain. Thus, around 90% of the overall labor and energy requirements are due to the harvesting and transportation operations of the supply chain. Average cost of biorefinery gate delivered corn stover biomass feedstock is estimated to be 121.9 \$-std. Mg^{-1} (110.6 \$-std. ton^{-1}), 30% of which is contributed by each harvesting and transportation operations. Cost to replenish nutrients removed from the field during stover harvest is the other major constituent of the overall supply chain cost contributing to around 20%. Furthermore, biorefinery gate delivered feedstock cost is identified to be the most sensitive to bale density followed by harvest rate, bale length, baler field efficiency and annual harvest days.

Comparing with gasoline on energy content per unit volume basis, biorefinery gate delivered feedstock cost will be around 69% of the ethanol price, which is significant. Thus, if not given serious consideration, feedstock price can be a limiting factor for the commercial deployment and sustainability of cellulosic biofuels. This component of the overall cellulosic biofuels production cycle requires further research to identify the ways to improve different supply chain system parameters. This study estimates the overall cost of corn stover biomass supply chain and its components as well as identifies the areas that need further improvement for developing a robust, cost-effective and sustainable supply chain. Additionally, this study presents some of the achievable strategies to reduce the overall supply chain cost and has demonstrated their implications on the overall cost savings. Analysis presented in this study can be used as a reference for further optimization of the overall corn stover biomass supply chain and to extend the analyses to the other feedstock types, including other agricultural residues, forest residues and annual and perennial energy crops.

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2.8 Supporting Materials

2.8.1 Overall costs of corn stover biomass feedstock supply chain

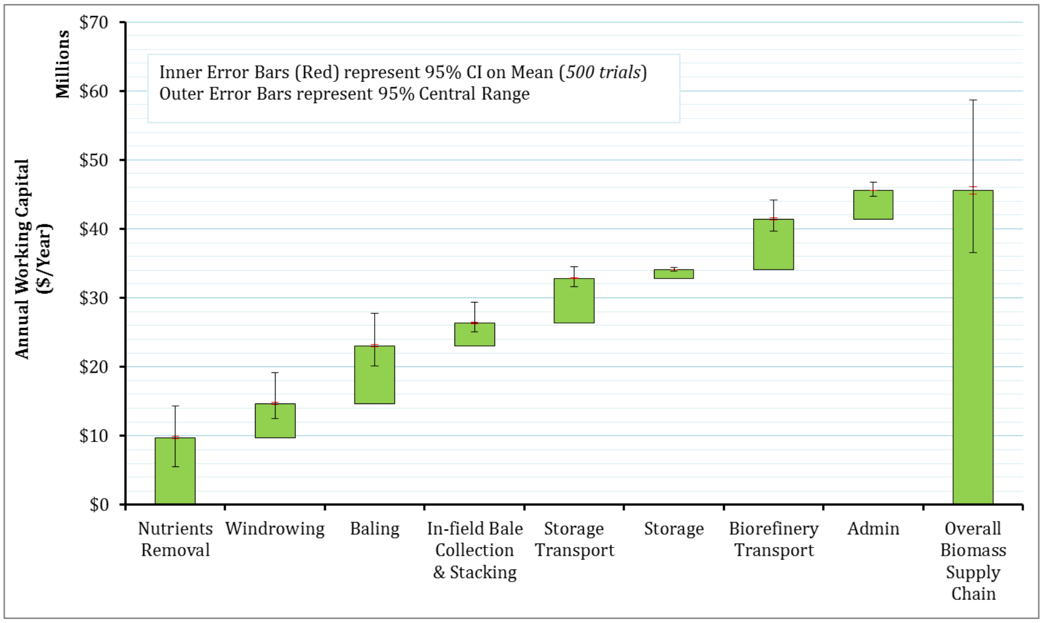


Figure S2.1: Annual working capitals for different processes of the corn stover biomass supply chain of a 114 MLPY (30 MGPY) biorefinery plant

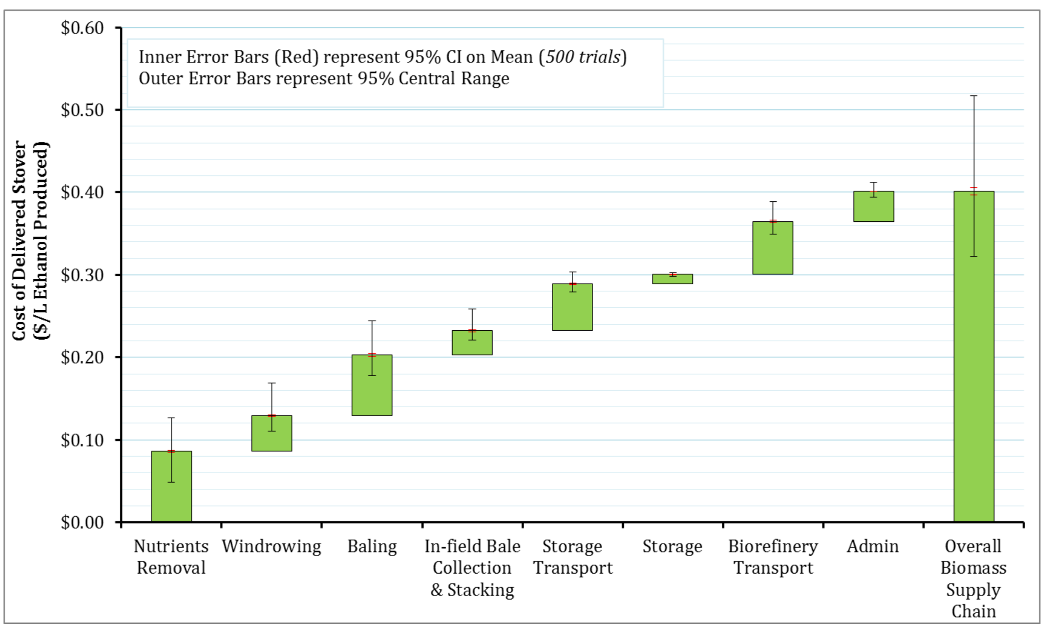


Figure S2.2: Cost of delivering stover to the gate of a 114 MLPY (30 MGPY) biorefinery plant to produce 1 L of cellulosic ethanol

2.8.2 Cost breakdowns for different components of the supply chain

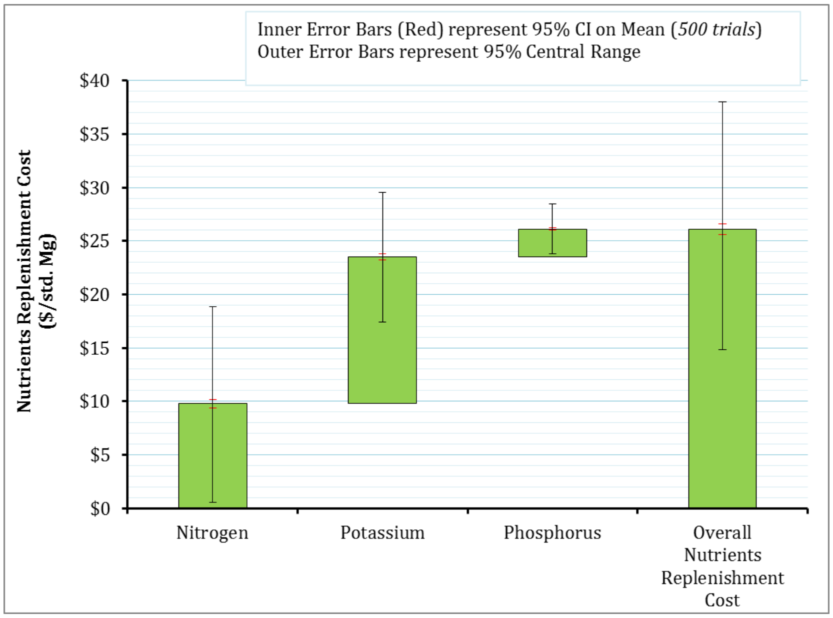


Figure S2.3: Nutrients replenishment cost of the corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

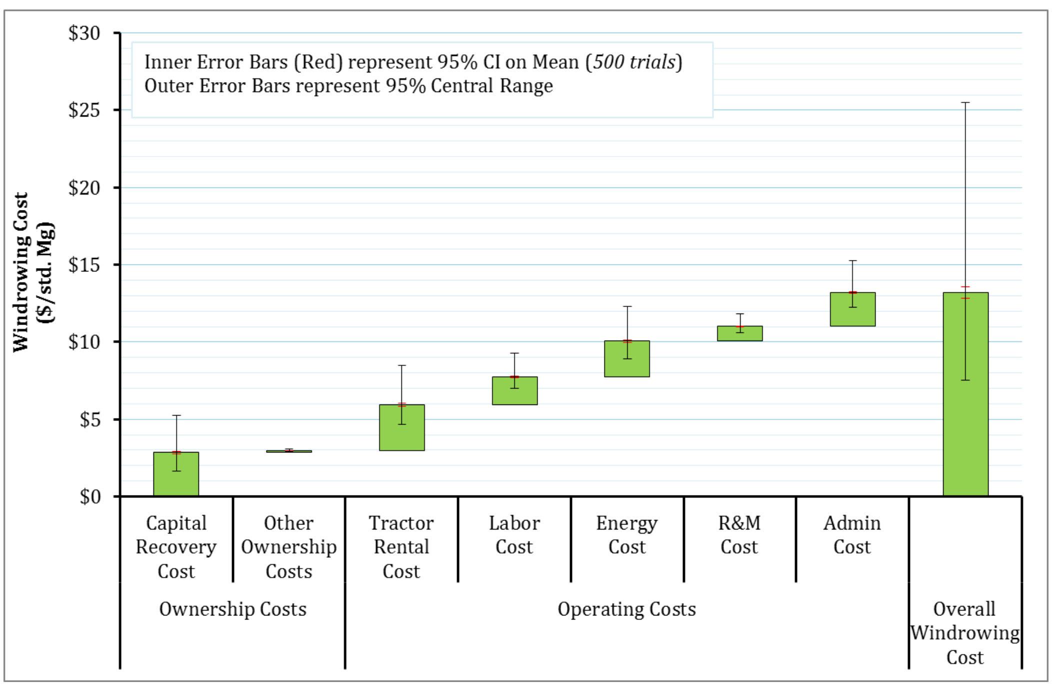


Figure S2.4: Windrowing cost of the corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

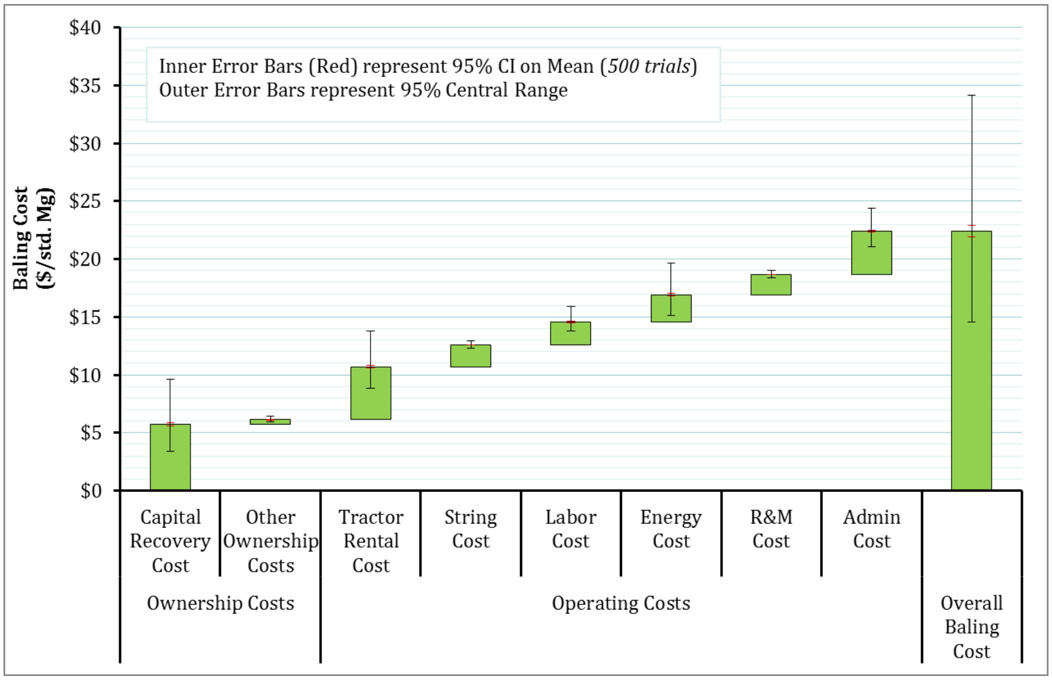


Figure S2.5: Baling cost of the corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

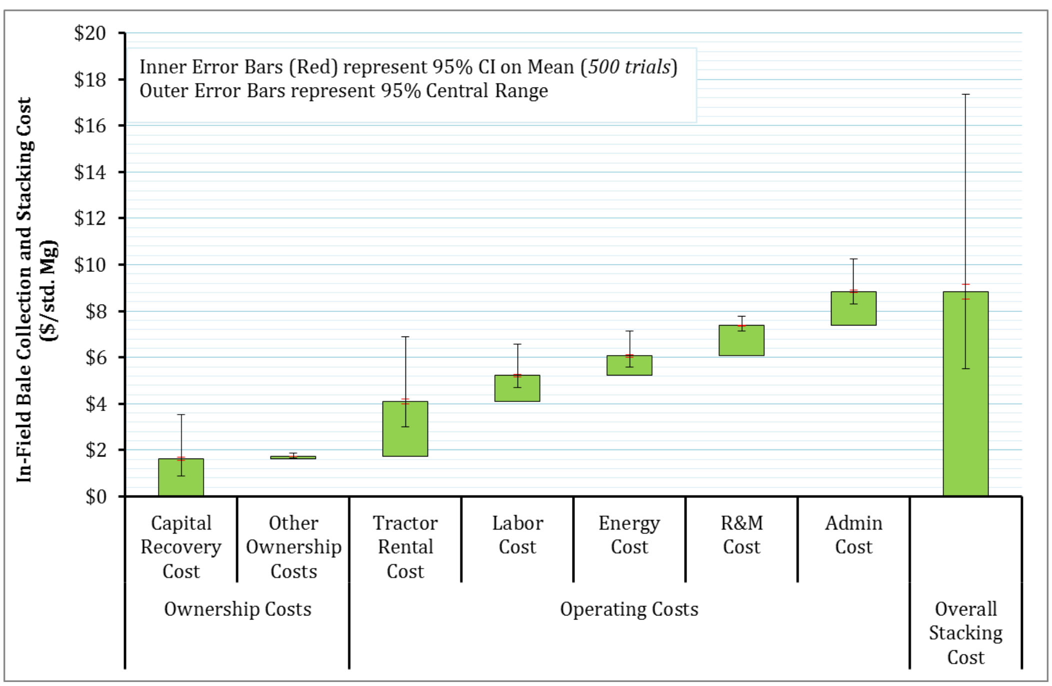


Figure S2.6: Stacking cost of the corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

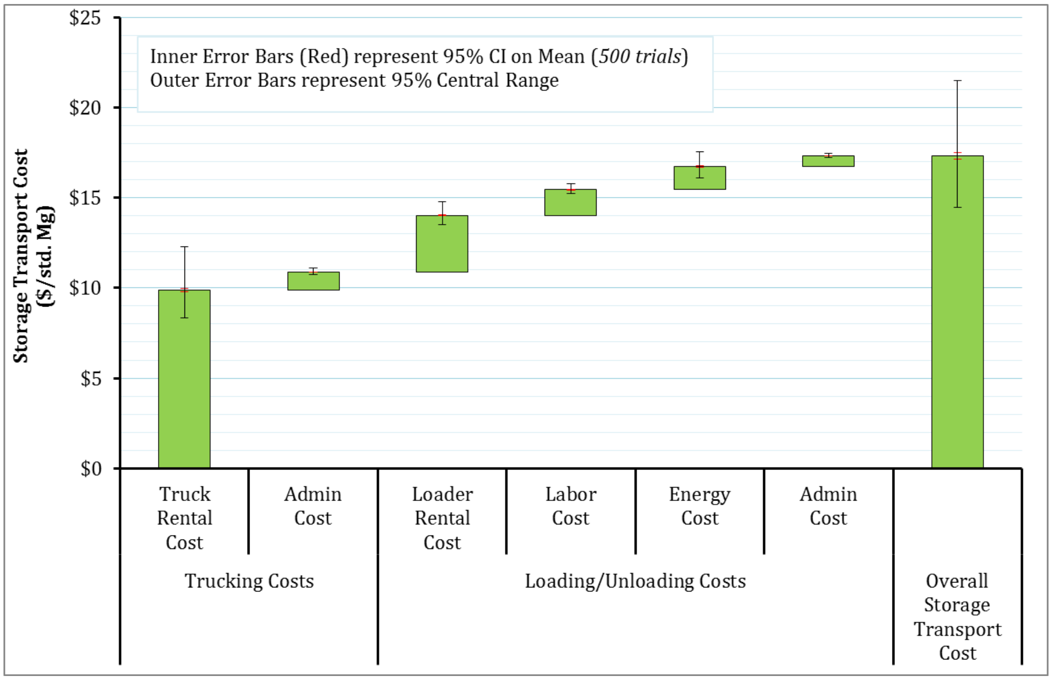


Figure S2.7: Storage transportation cost of the corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

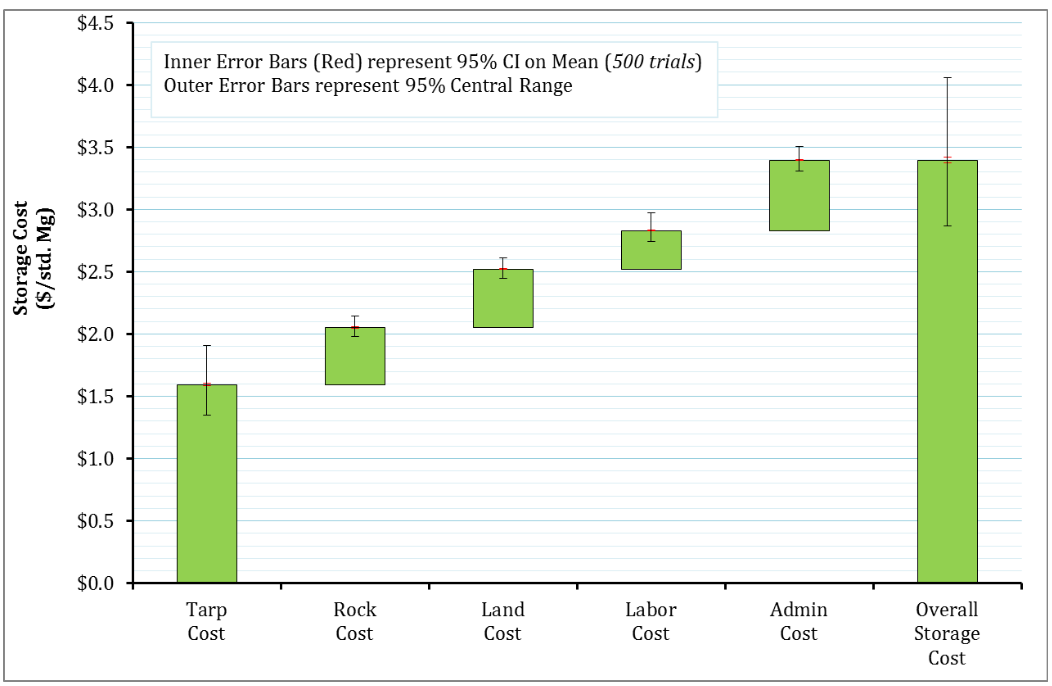


Figure S2.8: Storage cost of the corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

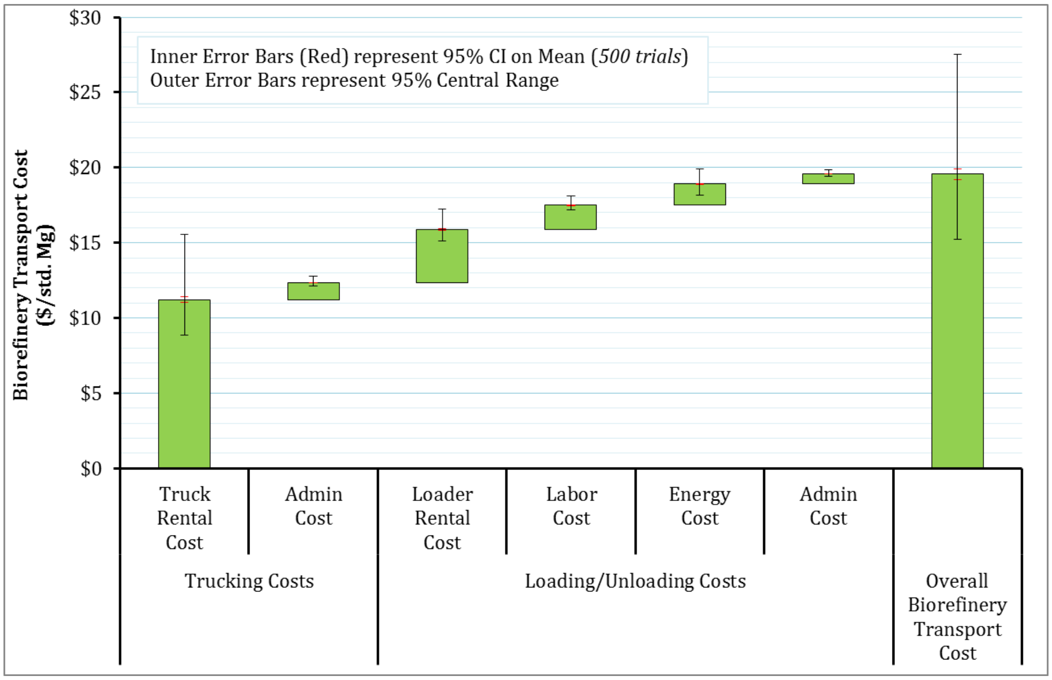
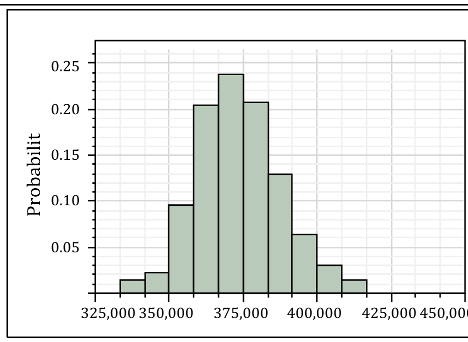
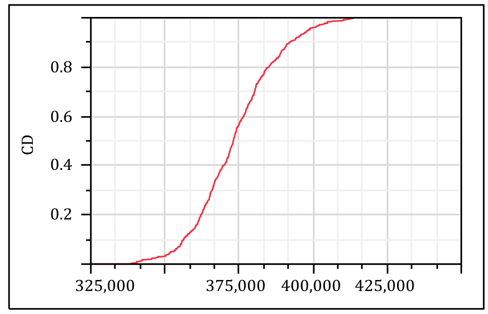
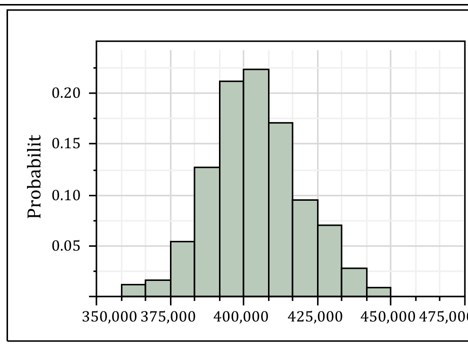
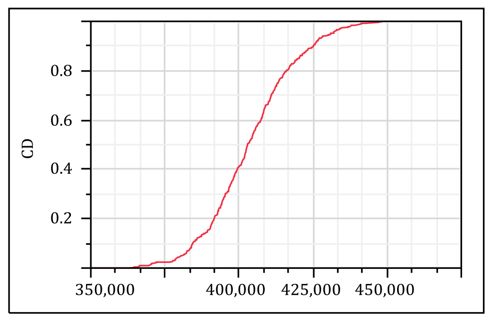
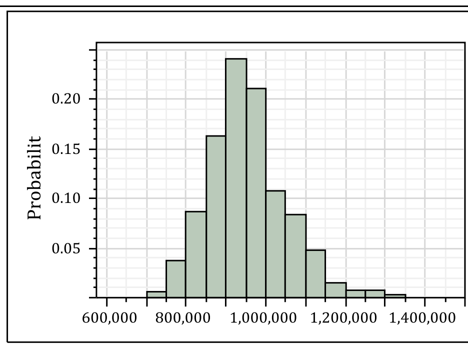
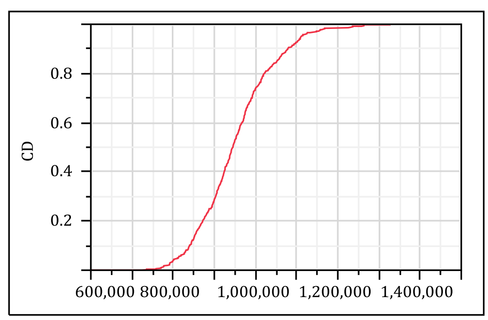


Figure S2.9: Biorefinery transportation cost of the corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

2.8.3 Histogram and cumulative distribution function (CDF) graphs of the main outcomes of this work, as discussed in the main body of the paper

Table S2.1: Histograms and CDF graphs of annual biomass feedstock demand and supply area for a 114 MLPY (30 MGPY) cellulosic biorefinery plant

Parameter	Histogram	CDF Graphs
Annual feedstock demand (std. Mg/ year)		
Annual harvest supply (std. Mg (har.)/year)		
Annual bale supply (bales/year)		

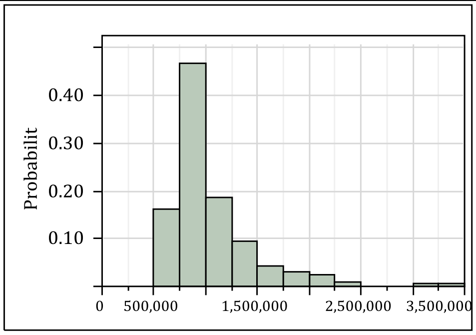
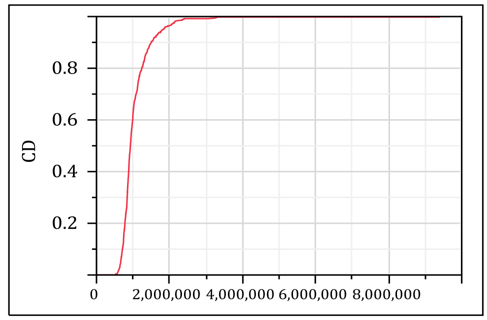
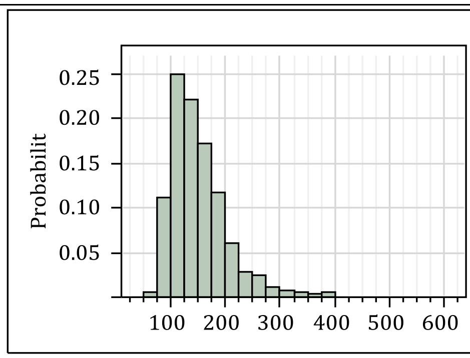
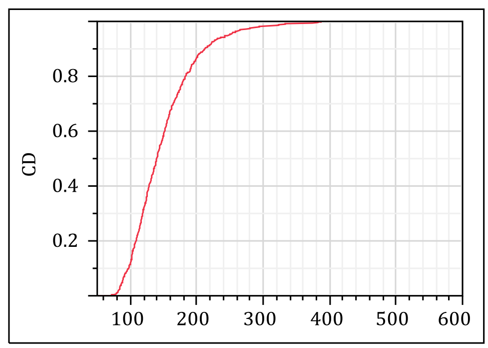
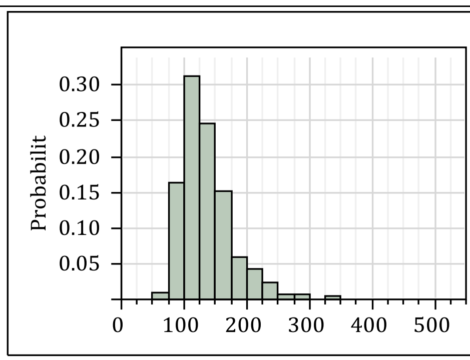
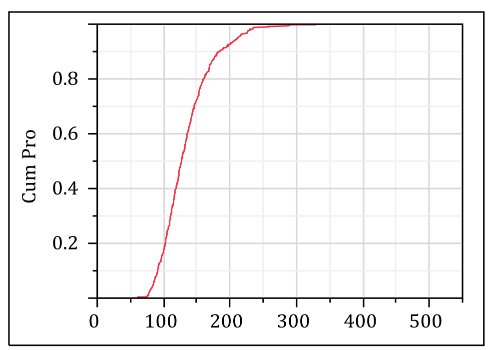
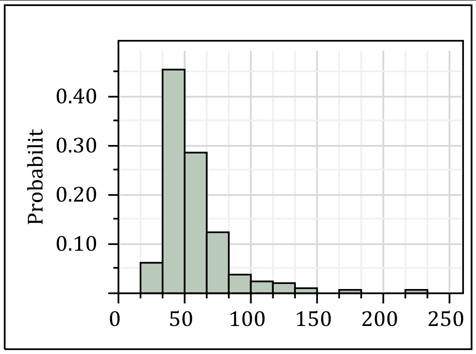
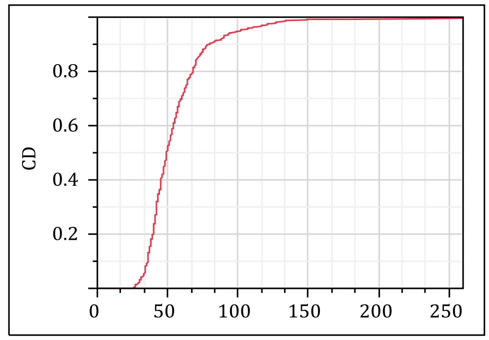
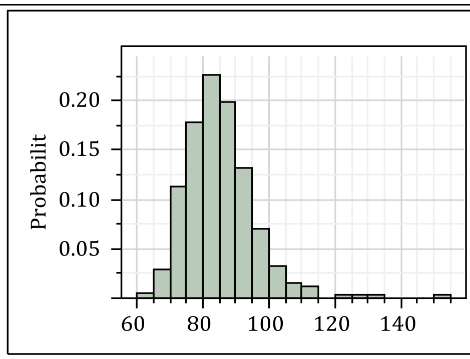
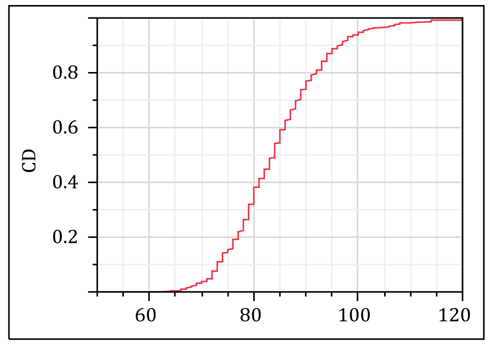
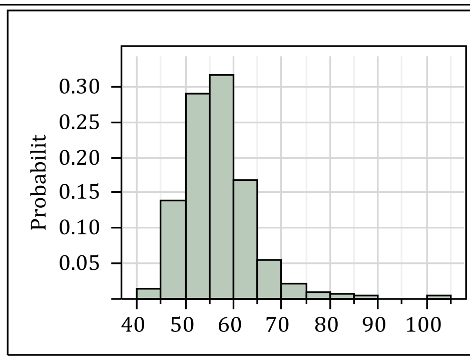
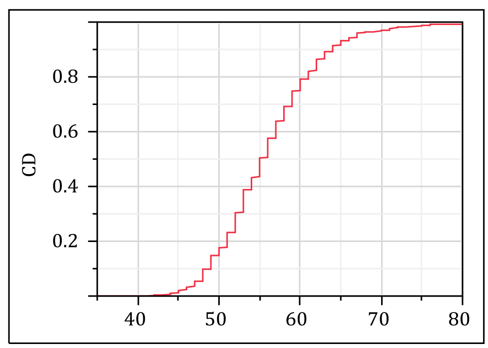
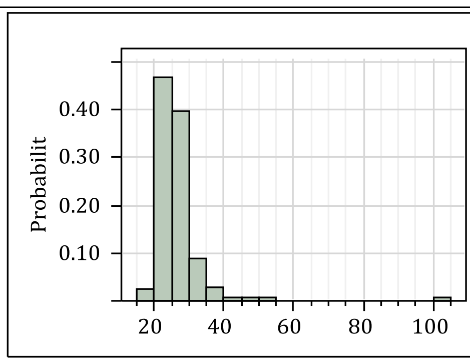
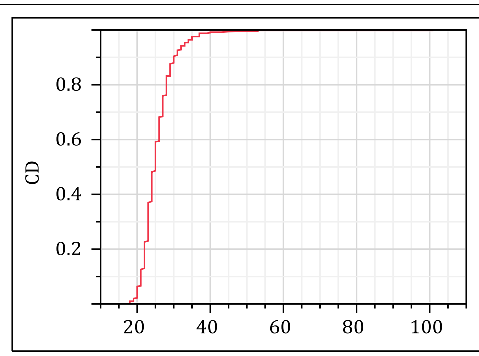
Parameter	Histogram	CDF Graphs
Annual feedstock supply area (ha/year)		

Table S2.2: Histograms and CDF graphs of annual machineries requirements for corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

Parameter	Histogram	CDF Graphs
Windrowers		
Balers		

Parameter	Histogram	CDF Graphs
Stackers		
Trucks for storage transportation		
Loaders for storage transportation		
Trucks for biorefinery transportation		

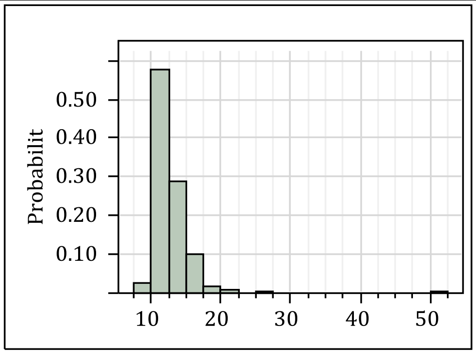
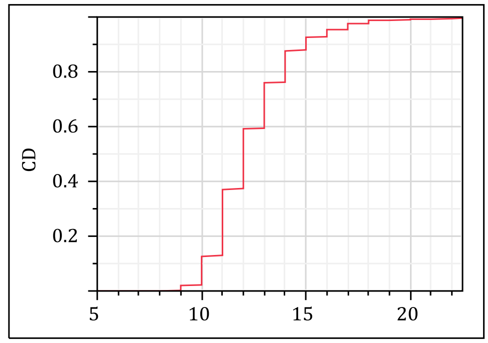
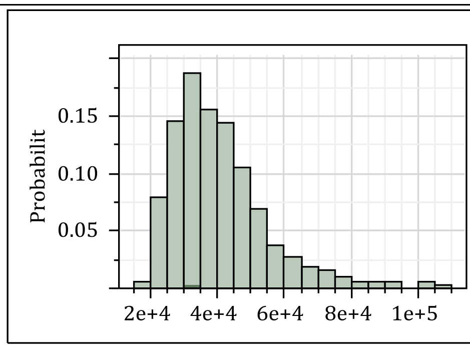
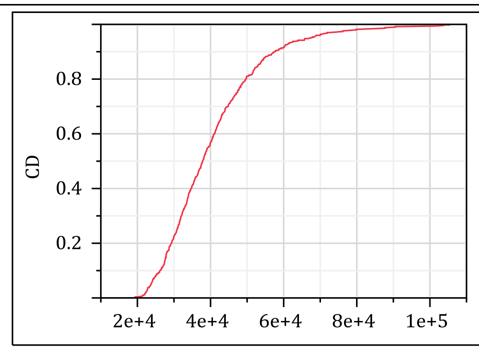
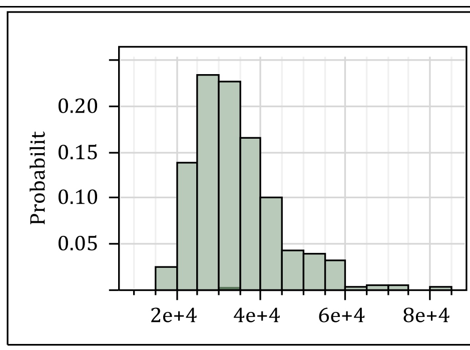
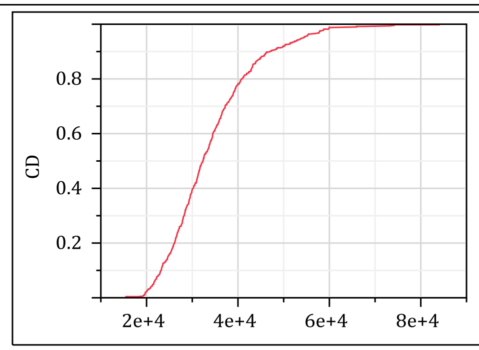
Parameter	Histogram	CDF Graphs
Loaders for biorefinery transportation		

Table S2.3: Histograms and CDF graphs of annual labor requirements (hour/year) for corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

Parameter	Histogram	CDF Graphs
Windrowing		
Baling		

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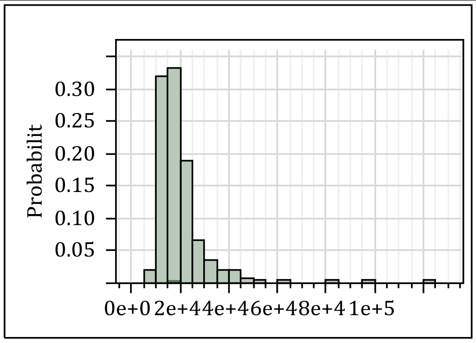
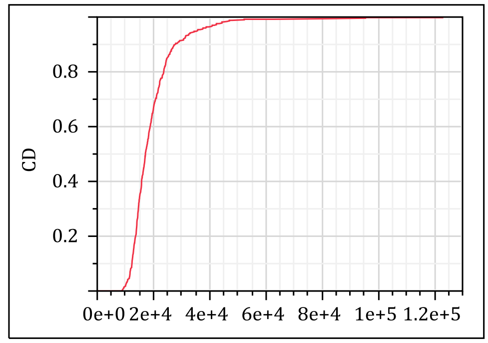
<tr><td>Stacking</td><td>
</td><td>
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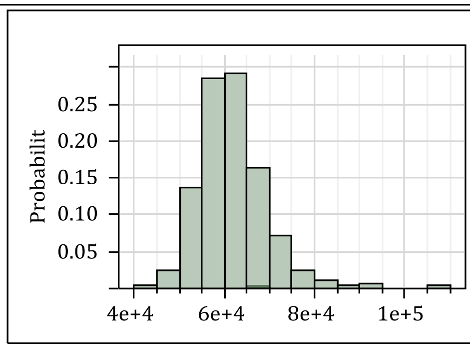
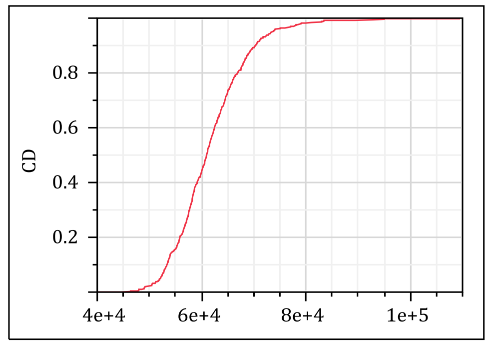
<tr><td>Storage transportation</td><td>
</td><td>
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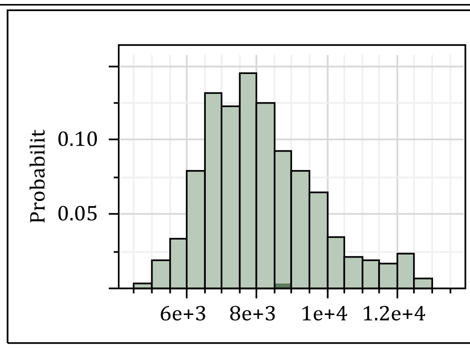
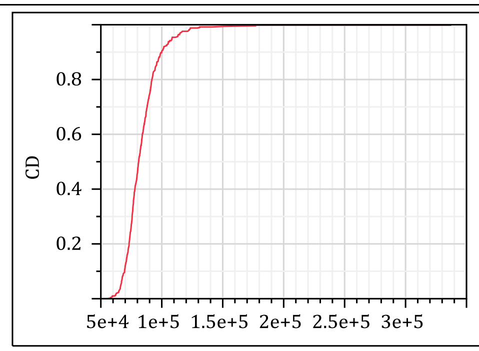
<tr><td>Storage</td><td>
</td><td>
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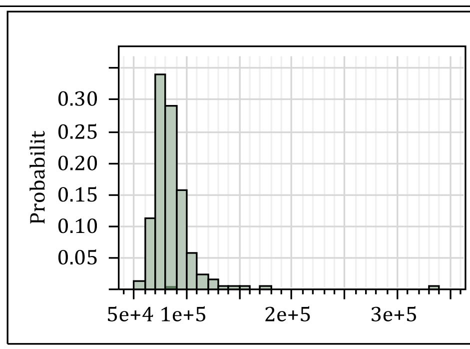
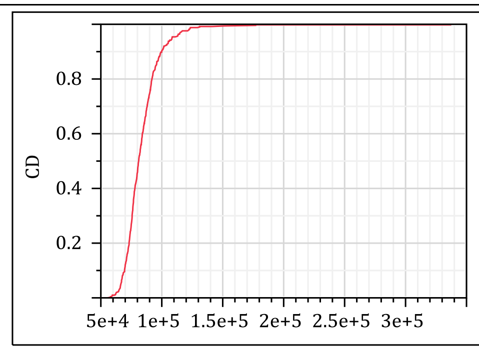
<tr><td>Biorefinery transportation</td><td>
</td><td>
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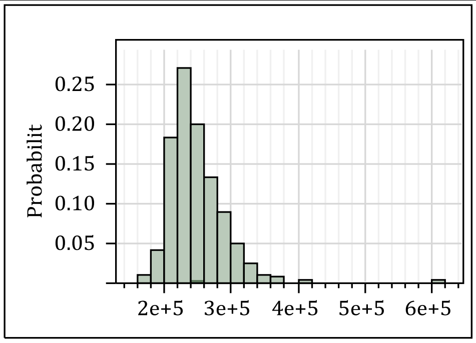
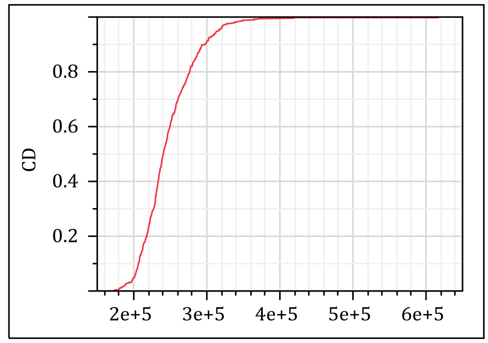
<tr><th>Parameter</th><th>Histogram</th><th>CDF Graphs</th></tr>
<tr><td>Entire supply chain</td><td>
</td><td>
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Table S2.4: Histograms and CDF graphs of annual fuel consumption (L/year) for corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

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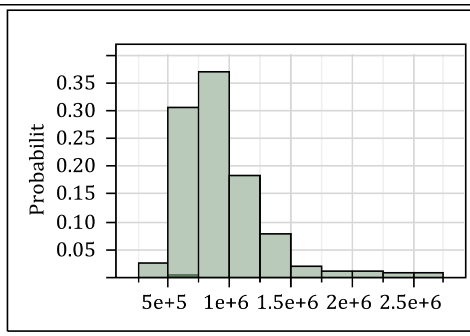
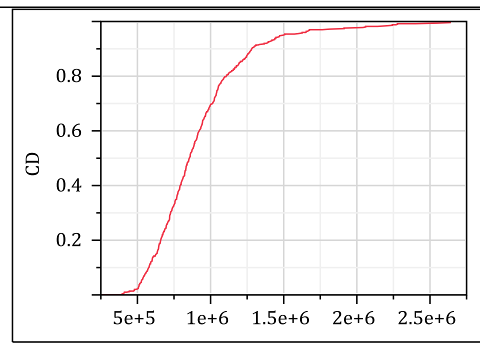
<tr><td>Windrowing</td><td>
</td><td>
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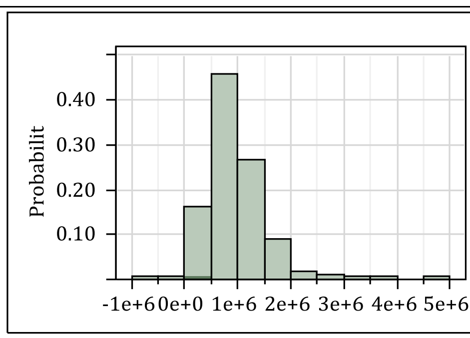
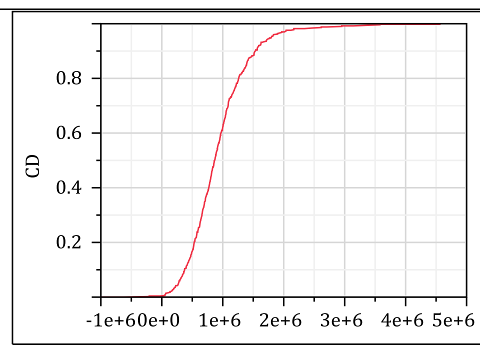
<tr><td>Baling</td><td>
</td><td>
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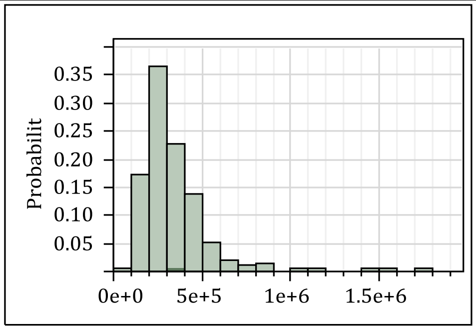
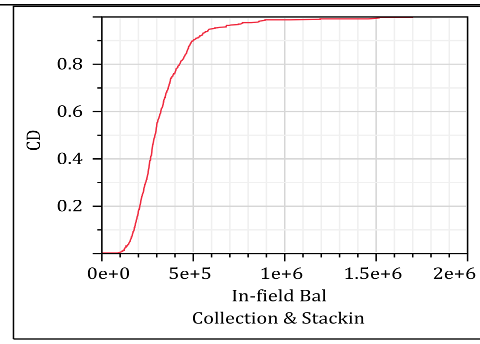
<tr><td>Stacking</td><td>
</td><td>
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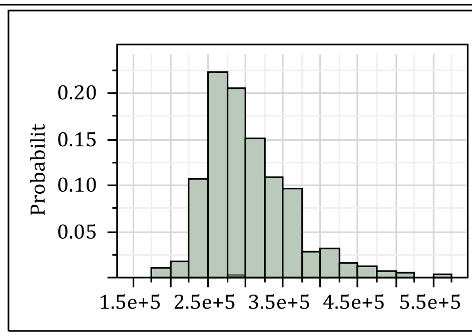
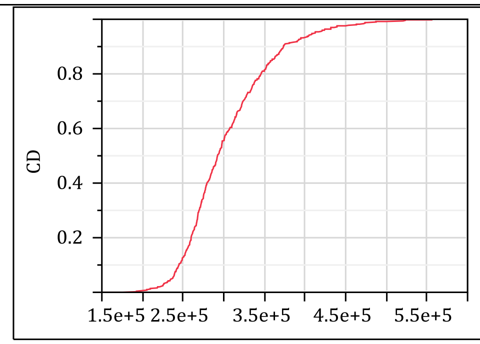
<tr><td>Trucks for storage transportation</td><td>
</td><td>
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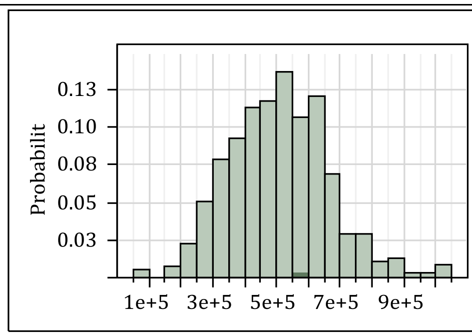
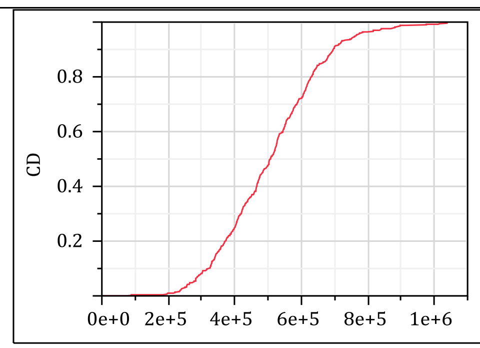
<tr><td>Loaders for storage transportation</td><td>
</td><td>
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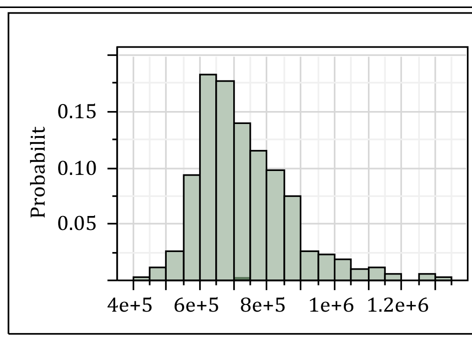
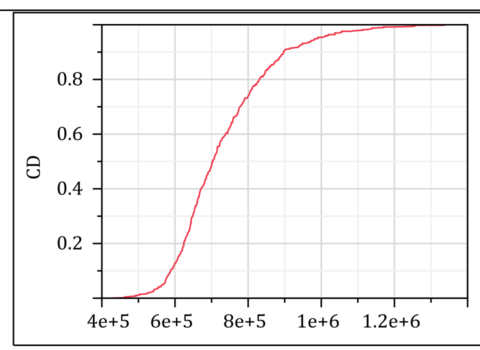
<tr><td>Trucks for biorefinery transportation</td><td>
</td><td>
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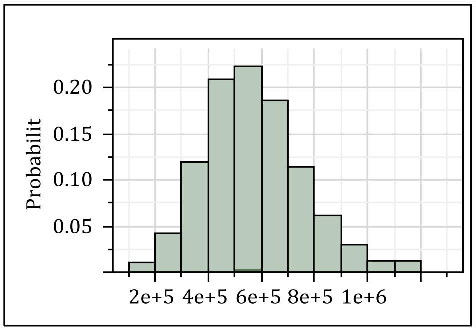
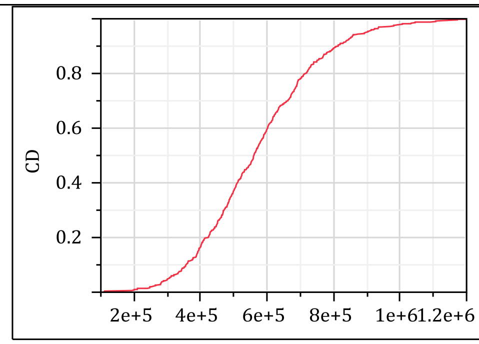
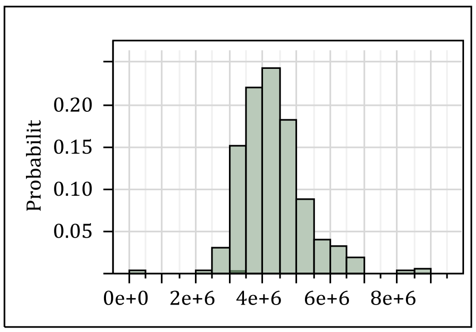
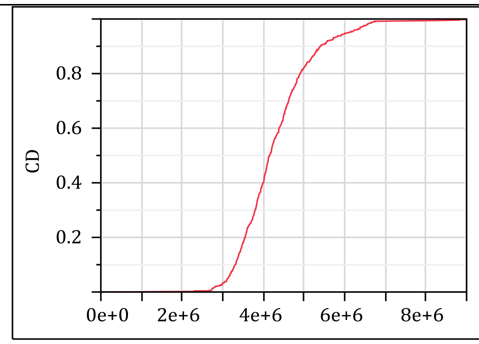
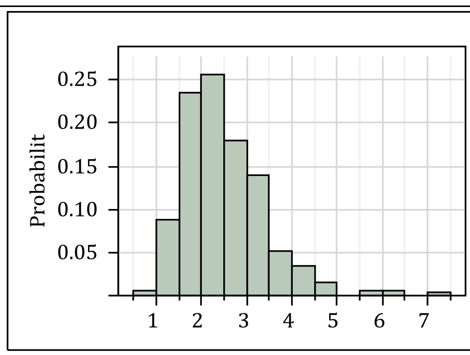
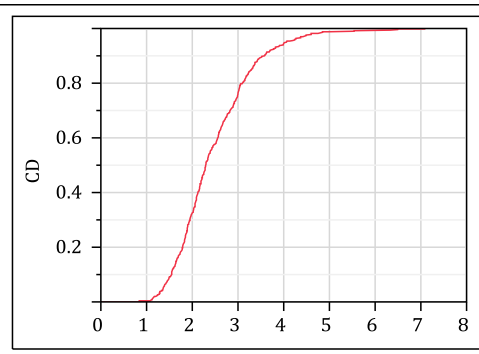
Parameter	Histogram	CDF Graphs
Loaders for biorefinery transportation		
Entire supply chain		

Table S2.5: Histograms and CDF graphs of fuel consumption (L/std. Mg) to deliver a std. Mg of stover to the gate of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

Parameter	Histogram	CDF Graphs
Windrowing		

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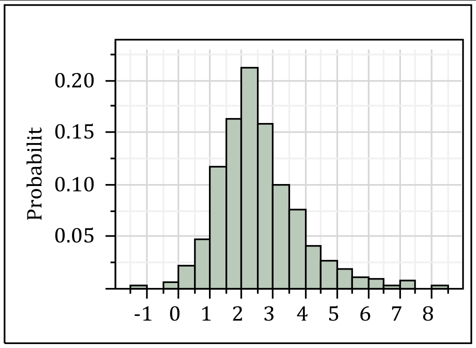
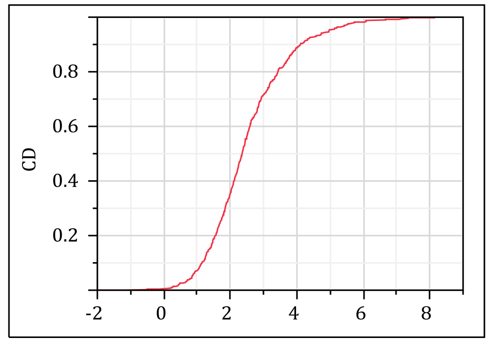
<tr><td>Baling</td><td>
</td><td>
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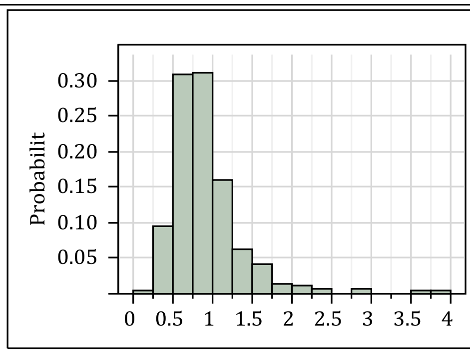
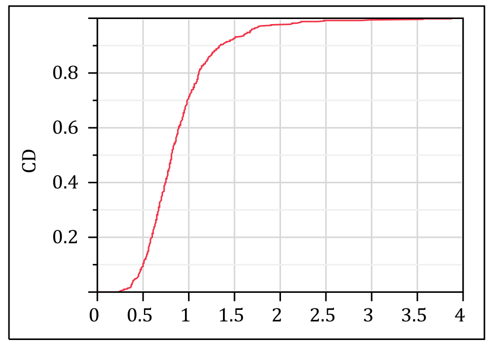
<tr><td>Stacking</td><td>
</td><td>
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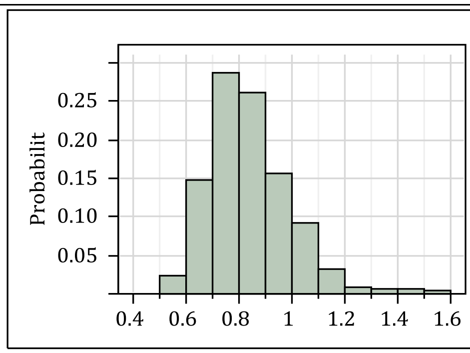
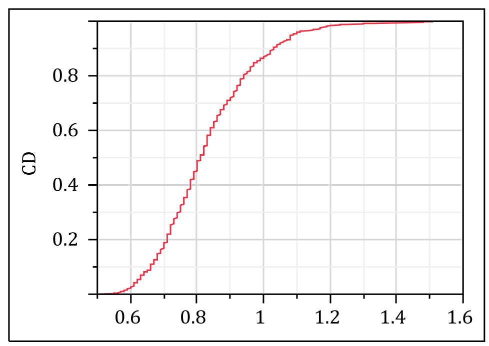
<tr><td>Trucks for storage transportation</td><td>
</td><td>
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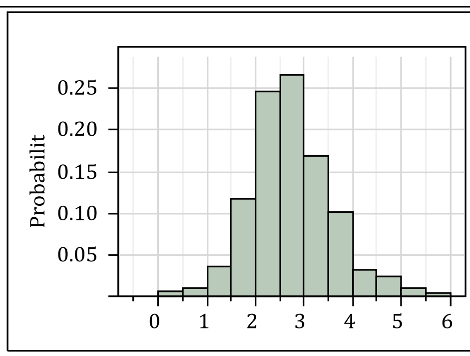
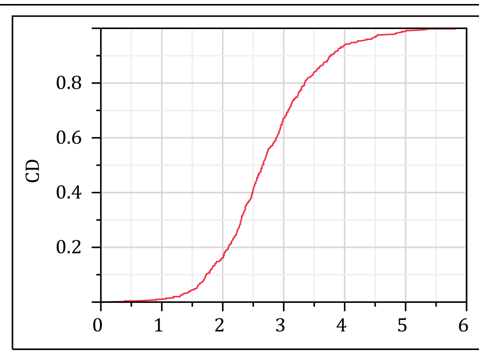
<tr><td>Loaders for storage transportation</td><td>
</td><td>
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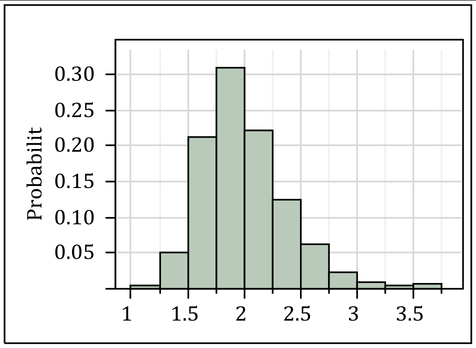
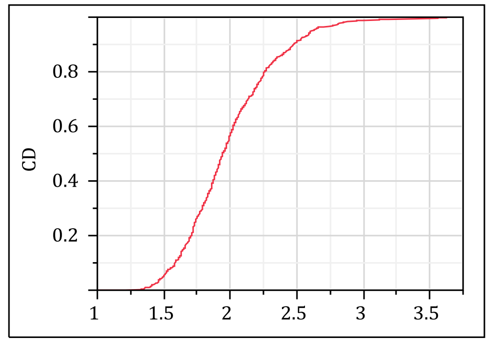
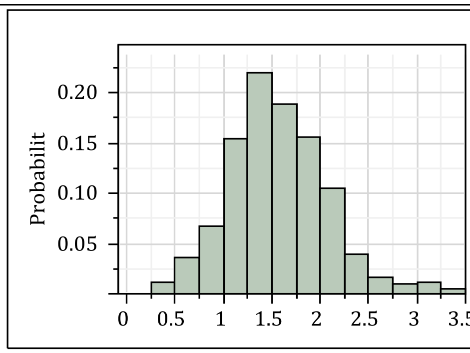
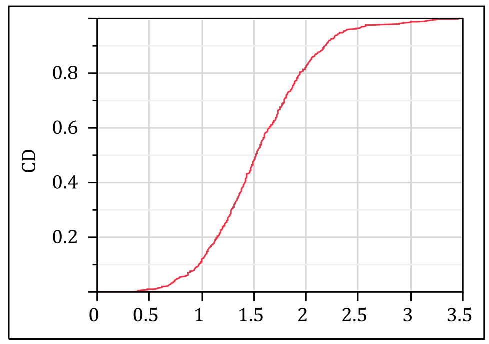
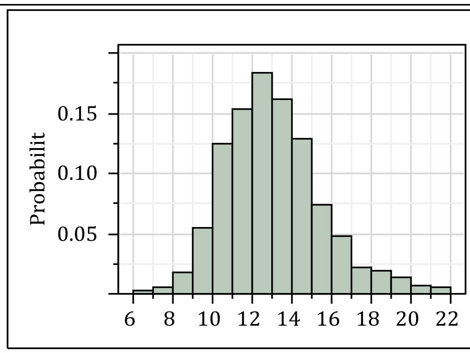
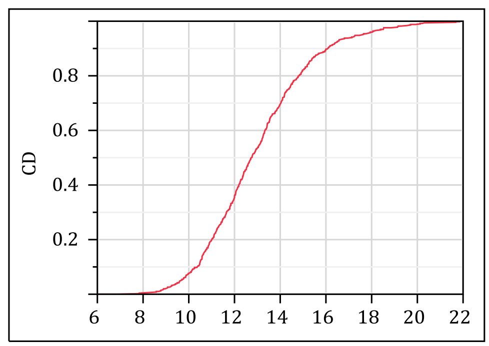
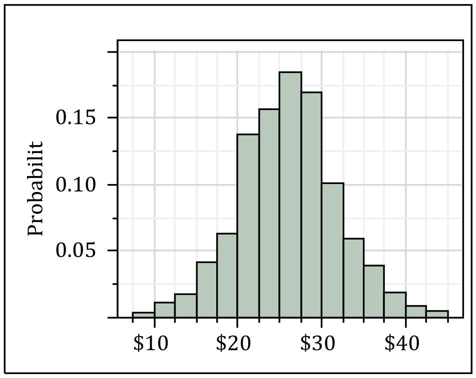
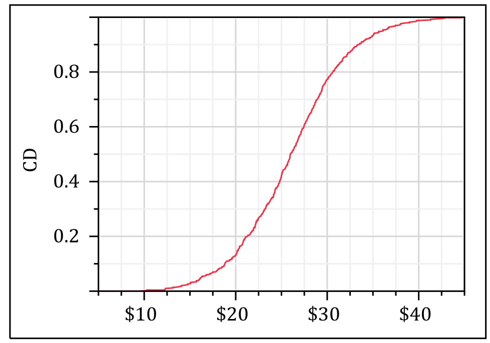
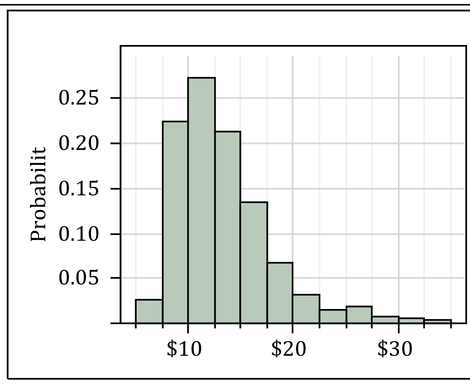
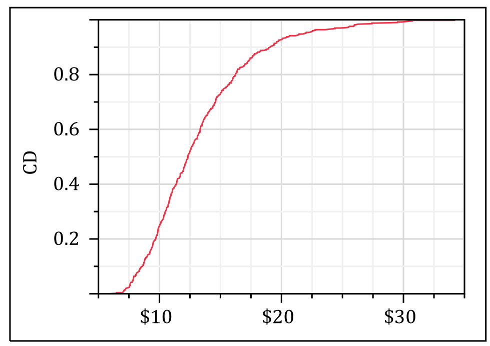
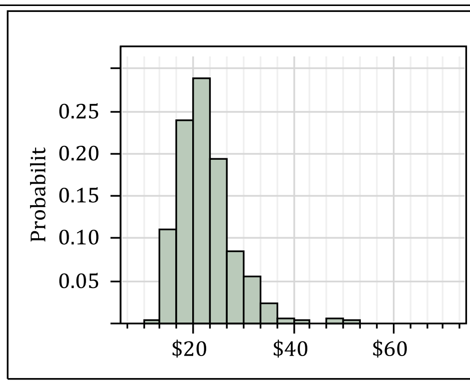
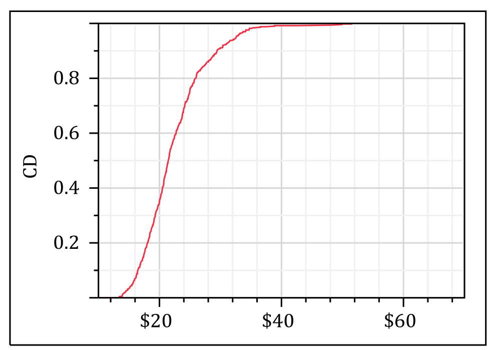
Parameter	Histogram	CDF Graphs
Trucks for biorefinery transportation		
Loaders for biorefinery transportation		
Entire supply chain		

Table S2.6: Histograms and CDF graphs of costs ($/std. Mg) to deliver a std. Mg of stover to the gate of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

Parameter	Histogram	CDF Graphs
Nutrients Replenishing		
Windrowing		
Baling		

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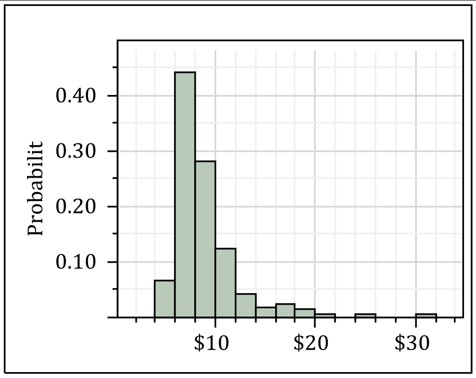
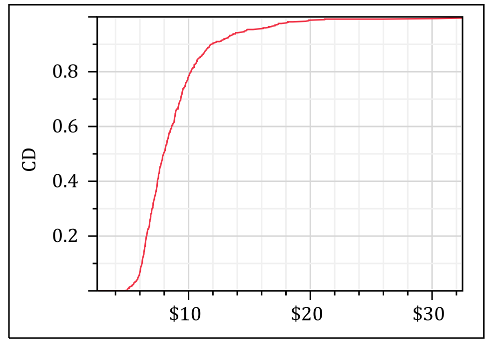
<tr><td>Stacking</td><td>
</td><td>
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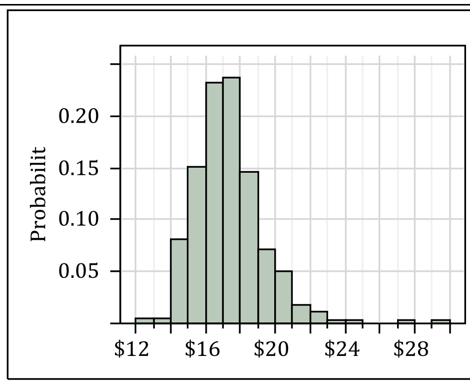
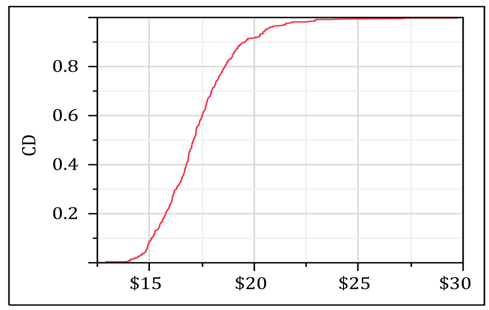
<tr><td>Storage transportation</td><td>
</td><td>
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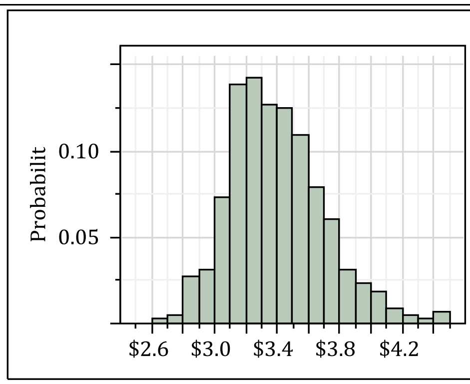
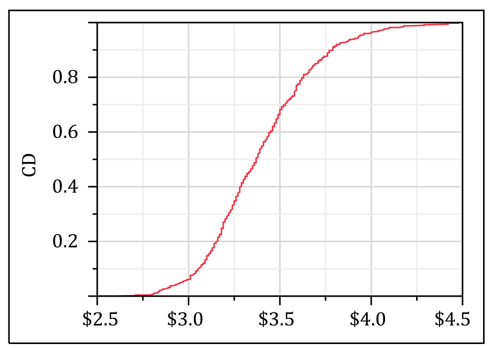
<tr><td>Storage</td><td>
</td><td>
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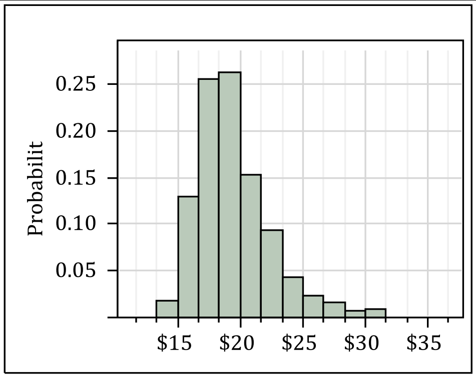
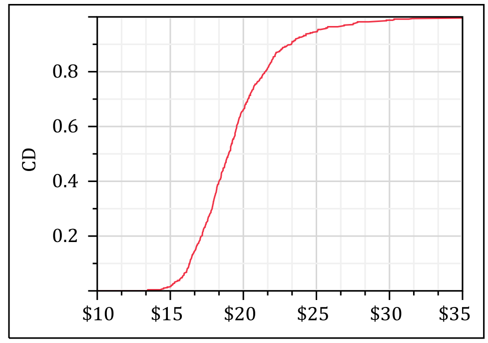
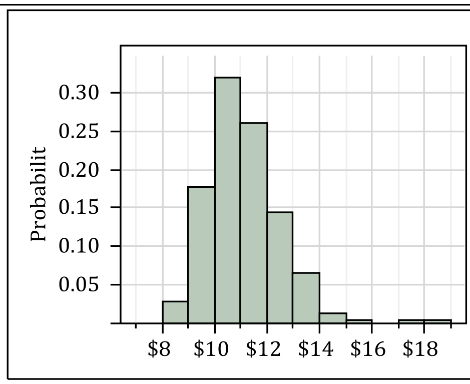
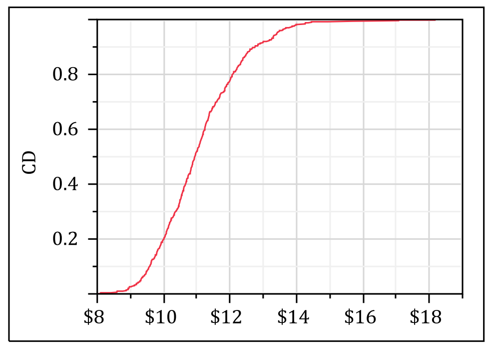
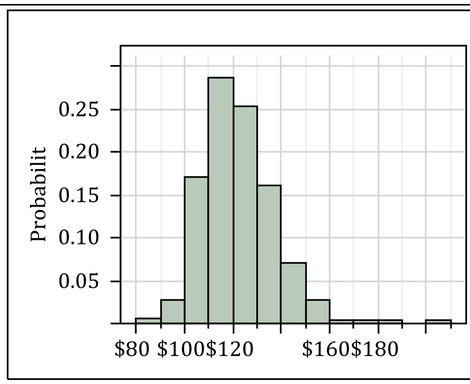
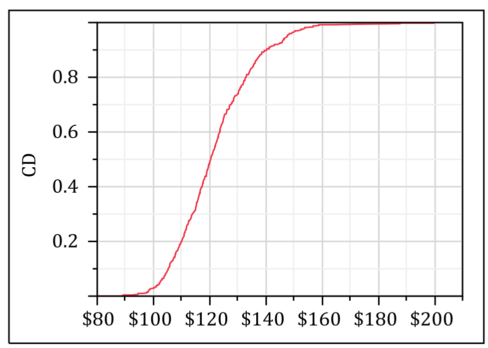
Parameter	Histogram	CDF Graphs
Biorefinery transportation		
Administrative costs for the overall supply chain		
Entire supply chain		

2.8.4 Sensitivity analysis results of the costs of different processes of the corn stover biomass feedstock supply chain

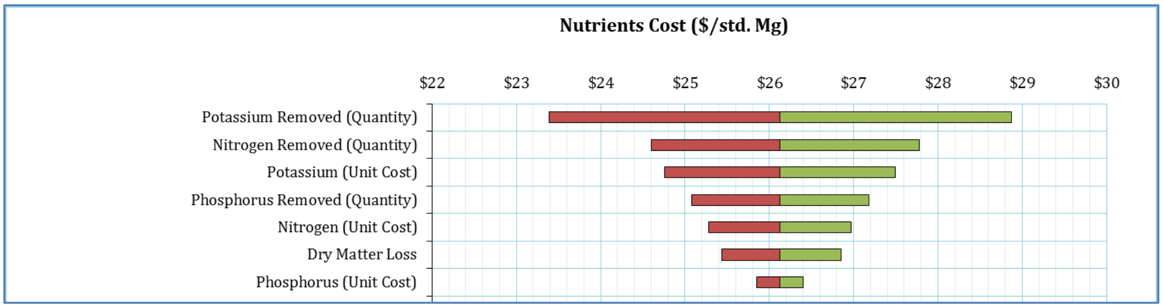


Figure S2.10: Sensitivity of nutrients replenishment cost of the corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

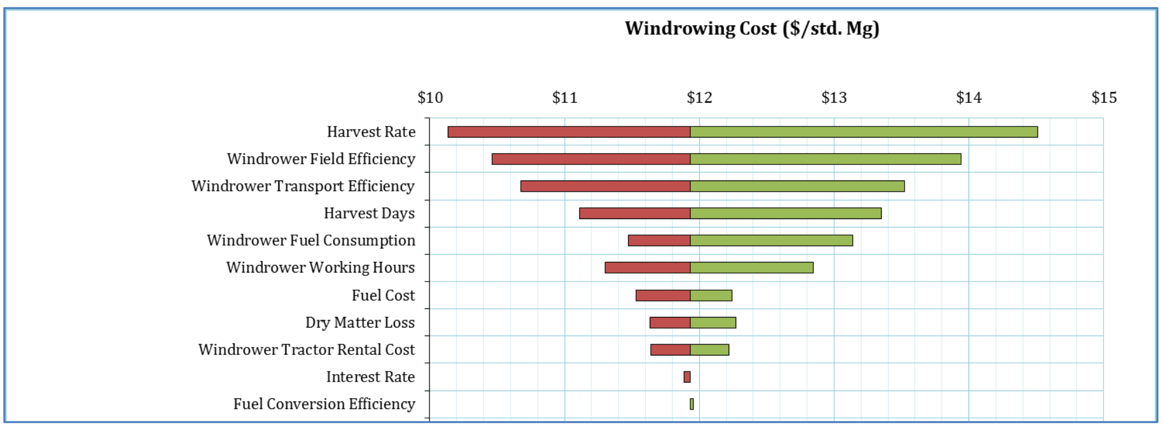


Figure S2.11: Sensitivity of windrowing cost of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

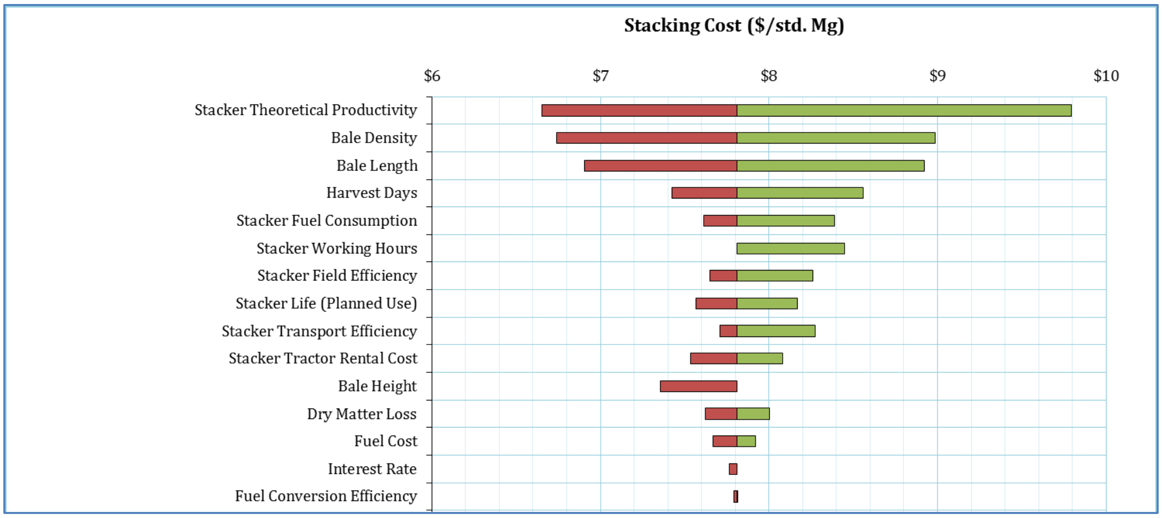


Figure S2.12: Sensitivity of stacking cost of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

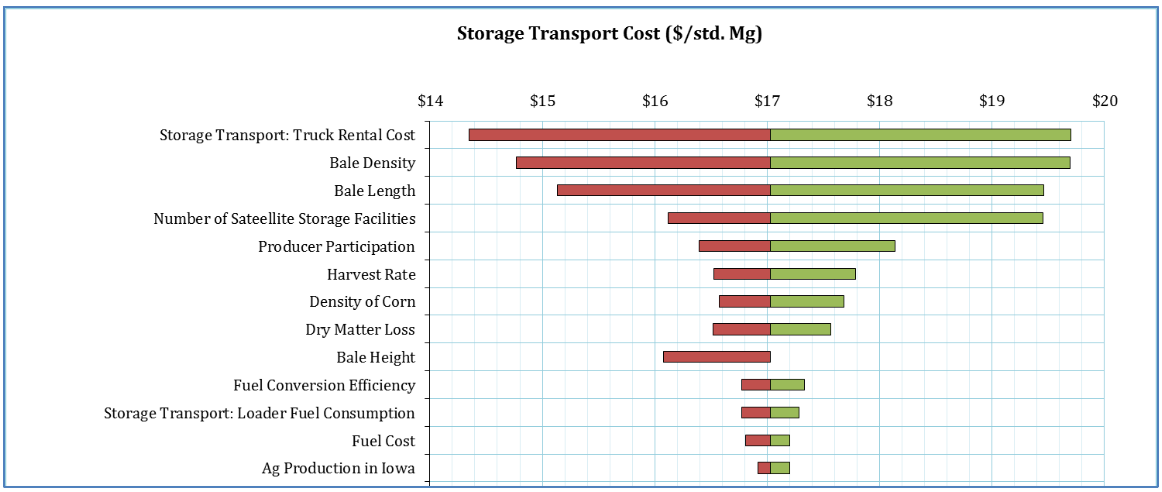


Figure S2.13: Sensitivity of storage transport cost of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

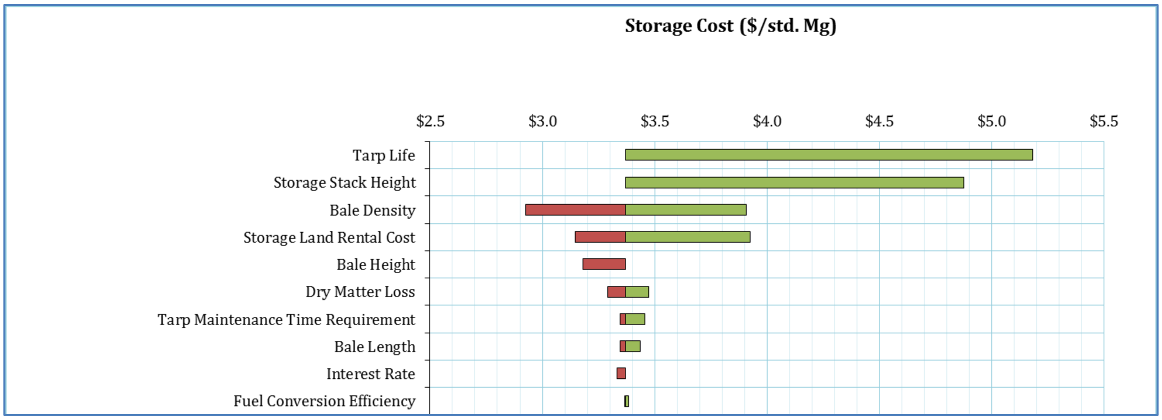


Figure S2.14: Sensitivity of storage cost of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

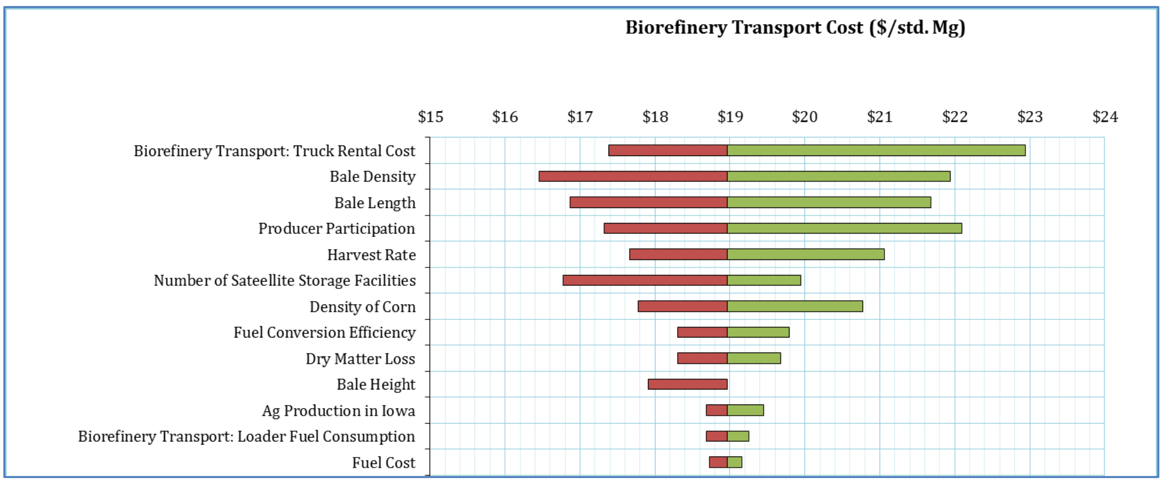


Figure S2.15: Sensitivity of biorefinery transport cost of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

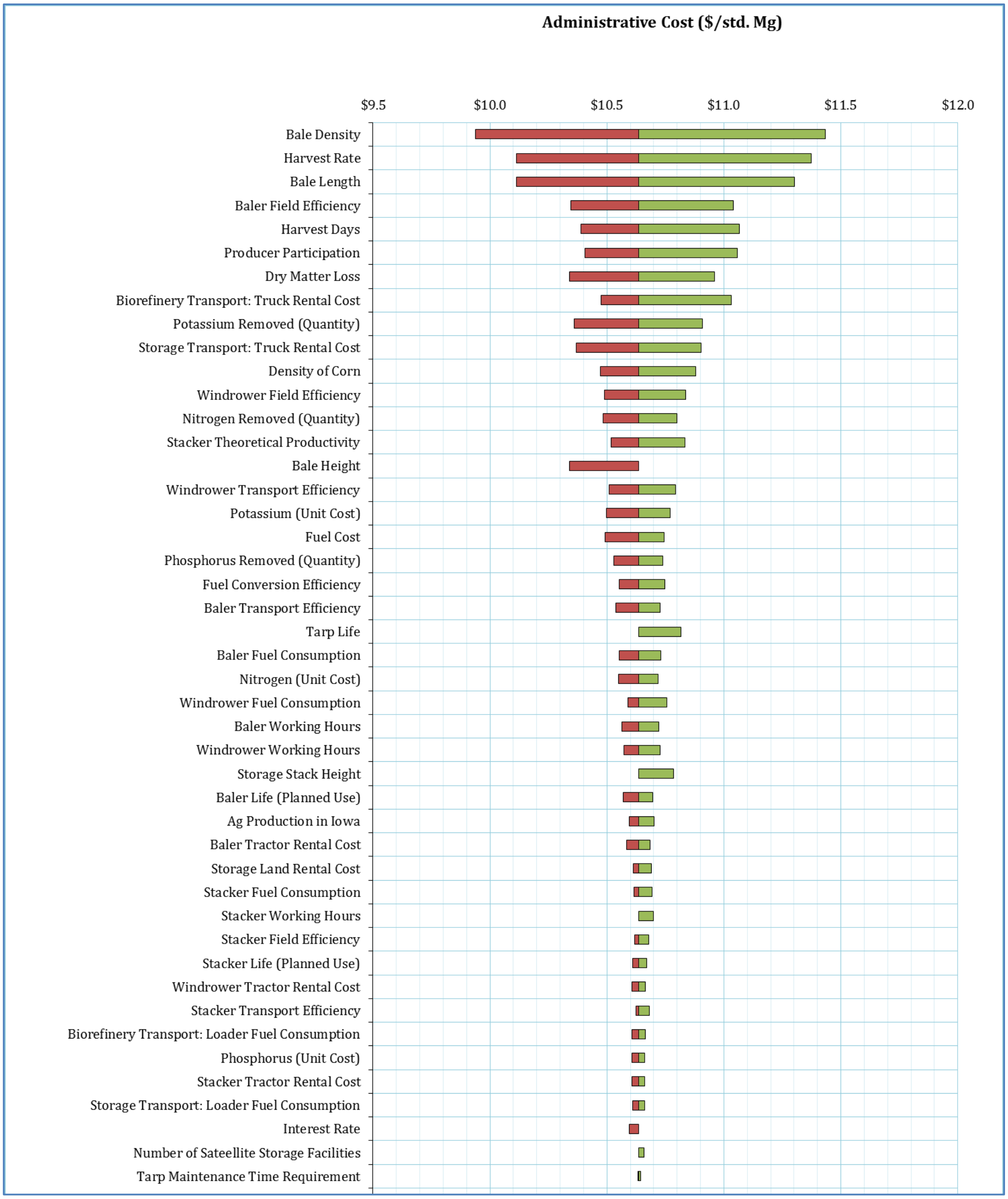


Figure S2.16: Sensitivity of administrative cost of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

CHAPTER III

LIFE-CYCLE ENERGY USE AND GREENHOUSE GAS EMISSIONS ANALYSIS OF THE CORN STOVER BIOMASS FEEDSTOCK SUPPLY CHAIN SYSTEM FOR A MIDWEST-BASED FIRST-GENERATION CELLULOSIC BIOREFINERY USING MULTIPLE YEAR PRODUCTION-SCALE FIELD DATA COLLECTED IN IOWA

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3.1 Abstract

Corn stover is the primary feedstock choice for most of the near-term first-generation cellulosic biorefineries in the Midwest, and their rated capacities are in between 76 and 114 million liter per year (MLPY) (i.e., 20 and 30 million gallon per year (MGPY)). Meeting feedstock demand of these biorefineries will require an annual feedstock supply of around 250-375 Mg (275-415 ton); however, literature lacks enough information to fully understand the ways to supply such an enormous quantity of feedstock to the biorefinery gate in an economic and environmentally sustainable manner. Thus, the main focus of this study is to stochastically evaluate the life-cycle energy use and greenhouse gas emissions (GHGE) for corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery in the Midwest by using production-scale experimental field data collected in Iowa. Different components of the selected supply chain includes harvesting (windrowing and baling), in-field bales collection and stacking at the field-edge, handling and transportation of bales from the field-edge to the distributed central storage facilities and, then, to the biorefinery plant, storage, and finally the audit of nutrients removed during stover collection from the field. Additionally, this study ranks different parameters based on their influence on the overall life-cycle energy use and GHGE for the supply chain. Average energy use, energy use ratio (EUR) and GHGE for corn stover feedstock supply chain of a Midwest-based 114 MLPY biorefinery plant are estimated to be 1502 MJ std. Mg^{-1} (1.3 million BTU std. ton^{-1}), 21%, and 95.2 kg-CO_2e std. Mg^{-1} (190.4 lb-CO_2e std. ton^{-1}), respectively. Nutrients removed during stover harvest shares 38 to 47% of the overall life-cycle energy use and GHGE for the supply chain, followed by harvesting (~24-28%) and transportation (~23-27%). Life-cycle GHGE and EUR are identified to be the most sensitive to quantity of nitrogen removed, bale density, bale length, harvest rate, baler field efficiency and dry matter loss.

Keywords: corn stover biomass feedstock supply chain, feedstock logistics, life-cycle assessment (LCA), Monte-Carlo simulation, sensitivity analysis

3.2 Introduction

Conventionally, corn stover, the non-grain aboveground fractions of the corn plant, is collected only in limited quantities from the field, primarily, to supply feed and provide bedding material for livestock. But, in recent years, with the advent of the federal policy mandating the production of cellulosic biofuels for blending into the fossil transportation fuels and to alleviate greenhouse gas emissions (GHGE), corn stover has been envisioned as the principal biomass feedstock for the future cellulosic biorefineries, mainly in the Midwestern United States. Revised Renewable Fuel Standard (RFS 2) authorized under the Energy Independence and Security Act (EISA) of 2007 mandates the production of 60.6 billion liter (16 billion gallon) of cellulosic ethanol by 2022. Even for 25% of this quantity to come from corn stover, with the biomass conversion efficiency of 300 L Mg^{-1} (~72 gal ton^{-1}) (Somerville et al., 2010), around 50 million Mg (~55 million tons) of dry stover would be required. Findings of updated Billion-Ton study (BTS) (DOE, 2011) suggest that U.S. has enough potential to supply this quantity of feedstock in an agronomically and ecologically sustainable manner. However, there exists a knowledge gap regarding how to supply such an enormous quantity of feedstock to the biorefinery gate in economic and environmentally sustainable manner. Chapter 2 of this dissertation focused on assessing the current techno-economic status of the corn stover feedstock supply chain having high-likelihood of industrial implementation by the first-generation cellulosic biorefineries in the Midwest. And, the main focus of this study is to assess the environmental status of the same supply chain in terms of life-cycle external energy use and greenhouse gas emissions (GHGE).

There are conflicting opinions over the merit of corn stover removal from the field with regards to its impacts on agricultural productivity, nutrients removal, soil organic carbon sequestration and air and water induced soil erosion (Blanco-Canqui and Lal, 2007; 2009; Cruse and Herndl, 2009; Hoskinson et al., 2007; Johnson et al., 2010; Karlen et al., 2011; Kim et al., 2009; Lindstrom, 1986; Mann et al., 2002; Nelson, 2002; Wilhelm et al., 2007; Wilts et al., 2004). Of particular relevance to this study is nutrients removed during stover harvest. Kim et al. (2009) compared the county level environmental performances of two continuous corn cropping scenarios, i.e., with and without stover removal, for various corn-growing locations in the U.S. Corn Belt, and found that harvesting corn stover reduces nitrogen-related emissions from the soil (i.e., N_2O, NO_x, NO_3^{-1}). Coulter and Nafziger (2008) found collecting stover in continuous corn to have potentials to raise the corn yields and lower nitrogen fertilization requirements. On the other hand, studies, including Johnson et al. (2010), Edwards (2011), to mention a few, have suggested the replenishment of nutrients removed during stover removal. Thus, it is essential to quantify the energy consumption and GHGE for different nutrients removed during stover collection from the fields, and is included within the scope of this study.

There are some studies focused on quantifying the energy use and GHGE for the corn stover feedstock supply chain; however, there exists variability in their reported estimates, mainly due to the selection of different system boundaries and the use of data from different sources. Among others, Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model developed by the researchers from Argonne National Laboratory is widely used for performing the life-cycle assessment (LCA) of transportation fuels and advanced vehicle technologies. Wang (1996) provides the details on the development and use of this model, and Wu et al. (2006) includes the details on the incorporation of corn stover to the GREET model. GREET is one of the most comprehensive transportation LCA models and uses data from other published works, thus, is more generalized. While GREET provides a thorough analysis of the entire cellulosic biofuels production and utilization in transportation activities, it doesn't consider storage, and assumes that corn stover will be transported directly from the field to the biorefinery plant; however, authors of this study believe that field-edge storage is not the viable option for handling the industrial quantities of corn stover required for cellulosic biorefineries, and, thus, requires storage at distributed facilities covering certain collection region. This further impacts the transportation process and requires two transportation events in contrast to one considered in GREET model. Additionally, GREET doesn't provide any detail on biomass handling equipment required during transportation. In addition to these, GREET incorporates data from various sources, most of which are based on small operations and in different geographic locations, and, thus fails to capture the impact of production-scale operations at certain region. However, if corn stover is to be the principal feedstock for cellulosic biorefineries in the Midwestern United States, it is necessary to quantity the life-cycle energy use and GHGE associated with its production and handling using the industrial-scale data collected in this region.

Morey et al. (2010) have generated deterministic life-cycle energy use and GHGE estimates for corn stover biomass feedstock supply chain for providing biomass to meet heat and power needs of a large-scale user such as a corn ethanol plant in the Midwest. They considered collecting corn stover from the field in round bale format and moving to the local storage sites within 3.2 km (2 mile) radius of the field during the fall harvest period, where bales would be ground and roll pressed before delivering to the plant within 48 km (30 mile) radius. Morey et al. (2010) has laid out a potential stover supply chain configuration, however, as is common with most high-level modeling solutions, their core assumptions are based on limited datasets, and, thus is not fully able to represent the scale required for the cellulosic biorefineries. Further details on GREET and Morey et al. (2010) along with their reported results are included in a later section of this paper.

Corn stover is the primary feedstock choice for most of the near-term first-generation cellulosic biorefineries in the Midwest, and their rated capacities are in between 76 and 114 million liter per year (MLPY) (i.e., 20 and 30 million gallon per year (MGPY)). Thus, this analysis evaluates life-cycle energy use and GHGE for corn stover biomass feedstock supply chain having high likelihood of industrial implementation by a 114 MLPY (30 MGPY) first-generation cellulosic biorefinery in the Midwest by implementing life-cycle assessment methodology using production-scale field data collected in Iowa. The supply chain considered in this study is comprised of corn stover harvesting (windrowing and baling), in-field bales collection and stacking at the field-edge, handling and transportation of bales from the field-edge to the distributed central storage facilities and, then, to the biorefinery plant, storage, and finally the audit of nutrients removed during stover collection from the field. Main supply chain parameters are supplied with probability distribution functions obtained from production-scale field tests conducted in Iowa, and their impacts on the life-cycle energy use and GHGE are stochastically estimated by employing Monte Carlo simulation method. In addition to these, sensitivity analysis is performed to identify the impacts of the main supply chain parameters on the life-cycle energy use and GHGE for the corn stover biomass feedstock supply chain, and to rank these parameters based on their relative influence on these metrics.

3.3 Methodology

3.3.1 Goal and Scope

The goal of this study is to estimate the life-cycle energy use and greenhouse gas emissions (GHGE) of corn stover biomass feedstock supply chain with high potential to be implemented by the first-generation cellulosic biorefineries. This analysis uses production scale field data collected in Iowa, so the geographical scope of this analysis is the central Midwestern United States. Different components of the corn stover supply chain configuration are selected based on their likelihood to be implemented by first-generation cellulosic biorefineries in the Midwest, and includes multi-pass corn stover harvesting (windrowing and baling), in-field bale collection and stacking at the field edge with the use of externally-powered pull-type wagon (referred to as '*stacking*' hereafter), transportation of stover bales from the field-edge to the central storage facilities in trucks with flatbed trailers facilitating the loading/unloading of bales to/from the truck trailers using squeeze loaders (combination referred to as '*storage transport*' hereafter) and, then, to the biorefinery plant (combination referred to as '*biorefinery transport*' hereafter), storage of stover bales with tarp cover, and finally the audit of nutrients (nitrogen, potassium and phosphorus) removed from the field due to corn stover harvest.

3.3.2 Function, Functional Unit and Reference Flow

The function of the feedstock supply chain analyzed in this study is to deliver corn stover biomass feedstock to the biorefinery gate, so, the functional unit is defined as the biorefinery gate delivered corn stover biomass in bale format, and the reference flow is 1 standard Mg (std. Mg) of biorefinery gate delivered stover. In this analysis 'Standard Weight' refers to the weight of corn stover having 0% moisture and 8% ash contents. In addition to this, energy use and GHGE estimates for a corn stover supply chain are made on 'per year' and 'per unit volume (L) of ethanol produced' basis. Furthermore, energy use estimates for the supply chain and its components are also presented in terms of ‘Energy-Use Ratio (EUR)’, which is the ratio of the external energy used by the feedstock supply chain to deliver stover to the biorefinery gate to produce cellulosic ethanol and the overall energy contained in the ethanol produced. For EUR estimation, energy content (higher heating value (HHV)) of ethanol is taken as 23.6 MJ/L (84,530 BTU/gal) (AFDC, 2013). This measure provides the indication of the energy intensity of feedstock supply chain. All these estimates account for dry matter loss (DML) for different processes of the supply chain. Although different estimates are made, results in ‘per std. weight (Mg)’ basis are mainly discussed throughout this paper. In addition to this, energy use ratio estimates are discussed in this paper. Other results are sometimes discussed in context and are included in the supporting material, as applicable. Further details of the life-cycle modeling of corn stover biomass supply chain for energy use and GHGE estimation are presented in the following sections.

3.3.3 Systems Boundary

All unit operations of corn stover feedstock supply chain between the start of harvesting and the point when the bale is delivered to the biorefinery gate are included within the system boundary of this study. Further details of the system have been included in Chapter 2 of this dissertation, which focuses on the techno-economic analysis of the same system. For machineries involved in windrowing, baling, stacking, and transportation activities, direct energy use and GHGE for their operation, and indirect energy use and GHGE (i.e., embedded energy and GHGE) during their manufacture and maintenance are estimated. Life-cycle energy use and GHGE estimates for the operation of machineries also includes life-cycle embedded energy and GHGE in fuel. Life-cycle energy use and GHGE associated with consumables used in different processes have also been estimated. In addition to these, life-cycle energy and GHGE embedded in nutrients (N, P and K) removed along with the stover during harvesting have been included within the system boundary for this analysis.

3.3.4 Data and Analysis

3.3.4.1 Life-cycle modeling overview

A macro-enabled spreadsheet-based model was developed to estimate the life-cycle energy use and GHGE for the corn stover biomass feedstock supply chain of a cellulosic biorefinery, explained earlier. Some of the main inputs to the model are tabulated in Table 3.1, and the values are mainly obtained from multiple-year production-scale field tests conducted on over 16,000 ha (~40,000 acres) of corn fields in Iowa. Additionally, the inputs are consistent with those used in chapter 2 of this dissertation. Both the techno-economic (Chapter 2 of this dissertation) and life-cycle modeling were carried out for the same feedstock supply chain system, thus, resources requirements (including machineries, fuel, labor, consumables, etc.) will be the same. These have been thoroughly discussed in chapter 2 of this dissertation, and will not be repeated here.

Table 3.1: Main inputs for the corn stover biomass feedstock supply chain life-cycle modeling

Parameters	*Values		
	Units	Average	Standard Deviation
[α] Biorefinery capacity	MLPY (MGPY)	113.6 (30)	
[ß] Fuel conversion efficiency	L Mg^{-1} (gal ton^{-1})	329.6 (79)	12.5 (3)
[Γ] Iowa land in agricultural production	%	86	
[Γ] Corn production density in Iowa	%	45	
[Σ] Producer participation	%	30	
[σ] Overall supply chain DML	%	7.5	2
[μ] Bale length	cm (in)	243.8 (96)	5.1 (2)
[μ] Bale width	cm (in)	121.9 (48)	
[μ] Bale height	cm (in)	86.4 (34)	
[μ] Bale density	std. kg m^{-3} (std. lb ft^{-3})	166.6 (10.4)	14.4 (0.9)
[τ] Harvest rate	std. Mg ha^{-1} (std. ton ac^{-1})	3.6 (1.6)	0.9 (0.4)
[Φ] Harvest window	days yr^{-1}	32	
[Φ] Windrowers working days	hr day^{-1}	8.5	
[μ] Windrower field efficiency	%	70	15
[μ] Windrower transport efficiency	%	85	5
[τ] Windrower fuel consumption	L hr^{-1} (gal hr^{-1})	23.1 (6.1)	3.4 (0.9)
[Φ] Baler working days	hr day^{-1}	8	
[μ] Baler field efficiency	%	50	12
[μ] Baler transport efficiency	%	90	2
[τ] Baler fuel consumption	L hr^{-1} (gal hr^{-1})	27.6 (7.3)	11.4 (3)
[Φ] Stacker working days	hr day^{-1}	11	
[τ] Stacker productivity (max.)	bales hr^{-1}	65	19.6
[μ] Stacker field efficiency	%	95	2
[μ] Stacker transport efficiency	%	90	2
[τ] Stacker fuel consumption	L hr^{-1} (gal hr^{-1})	17.4 (4.6)	3.8 (1)
Loader fuel consumption	L hr^{-1} (gal hr^{-1})	20.8 (5.5)	5.7 (1.5)
[Φ] Total satellite storage sites		13	
[Φ] Storage transport working days	days yr^{-1}	55	
[Φ] Storage transport daily working hours	hr day^{-1}	8	
[Φ] Biorefinery transport working days	days yr^{-1}	280	
[Φ] Biorefinery transport daily working hours	hr day^{-1}	8	
[μ] Nitrogen removed with stover	kg-N Mg^{-1} (lb-N ton^{-1})	7.7 (15.4)	0.3 (0.6)
[μ] Phosphorus removed with stover	kg-P_2O_5 Mg^{-1} (lb-P_2O_5 ton^{-1})	2.5 (5)	1.1 (2.2)
[μ] Potassium removed with stover	kg-K_2O Mg^{-1} (lb-K_2O ton^{-1})	12.5 (25)	3.5 (6.9)

* Units and values in parentheses are in U.S. customary units

[α] Modeling input

ß Humbird et al. (2011); Standard deviation assumed

Γ using data from State Data Center of Iowa (2013) and Iowa Department of Agriculture (2013)

Σ A survey conducted by Tyndall et al. (2011) among Iowa farmers showed that 17% of Iowa's farmers had interest in harvesting their stover as a feedstock for cellulosic biorefineries, with 37% being undecided. Assuming 13% more farmers, among undecided, would decide on harvesting their stover for biofuels productoin, farmer participation has been taken as 30%.

σ Darr and Shah (2012) suggests 6% DML for tarped storage. Additional 1.5% has been considered for the loss in other processes of the supply chain. Standard deviation for DML is usually high (unpublished data suggests this to be in the range of around 6 percent points); however, for stable supply chain configuration, standard deviation should be minimal. Thus, this analysis considers 2% points standard deviation.

μ Darr, unpublished data

τ Data from Peyton (2012)

Φ Multiple years field experience by Darr research group at ISU

3.3.4.2 Life-cycle energy use and greenhouse gas emissions associated with off-road farm machineries and on-road trucks

Off-road machineries involved with the stover supply chain considered in this study include shredder with tractor for windrowing, large rectangular baler with tractor, pull-type multiple bale collection wagon with tractor for stacking, and squeeze loaders for loading/unloading bales to/from trucks during storage and biorefinery transports. For different off-road farm machineries and on-road trucks, life-cycle energy use and GHGE are estimated for their manufacture, maintenance and operation, and has been discussed in the following sections.

3.3.4.2.1 Life-cycle energy use and greenhouse gas emissions associated with the manufacture and maintenance of off-road farm machineries and on-road trucks

Life-cycle energy use and GHGE associated with the manufacture and maintenance of the off-road farm machineries and trucks are estimated on a 'steel-mass' basis. This approach has been used by other researchers, and assumes that these equipment are made entirely of steel. Hill et al. (2006) used the value of 25 MJ kg^{-1} (10,748 BTU lb^{-1}) for producing steel, and have assumed that an additional 50% energy would be required for the assembly of the equipment. The specifications of different equipment used for data collection in this study through different field tests are summarized in Table 3.2. And, the overall energy consumption (MJ std. Mg^{-1} of stover collected) associated with the manufacture of these equipment are estimated using these information along with their productivities (as estimated in chapter 2 of this dissertation), useful lives and weights (Table 3.2).

*Table 3.2: Details of off-road farm machineries and on-road trucks used for different operations of corn stover feedstock supply chain.

Farm Machineries	Make	Model	Capacity/ Type	ßUseful Life	αWeight
Windrower (Shedder)	Hiniker	5620	6 m (20 ft)	2,000 hr	2.8 (6,105)
Tractor for windrower	CIH	MX140	104 kW (140 hp)	10,000 hr	5.8 (12,800)
Baler	AGCO/Massey Ferguson	2170XD	0.9 x 1.2 m (3 x 4 ft)	75,000 bales	9.7 (21,500)
Tractor for baler	AGCO	MT665C	186 kW (250 hp)	10,000 hr	11.0 (24,250)
Stacker	ProAG	16K Plus	12 Bales	100,000 bales	5.9 (13,000)
Tractor for stacker	CIH	225	168 kW (225 hp)	10,000 hr	9.7 (21,500)
Squeeze loader	Stinger		6 bales	100,000 bales	0.2 (500)
Tractor for loader	John Deere	8245R	183 kW (245 hp)	10,000 hr	11.7 (25,868)
Semi-truck (combined tractor and trailer)			Class 8	800,000 km (500,000 mi)	11.3 (25,000)

* Trade names are mentioned solely to provide specific information and do not imply endorsement of the products by the authors or Iowa State University and the research collaborators.

α Weights in units of 'Mg' with that in units of 'lb' in parentheses. Weights of off-road farm machineries are taken from the commercial websites of the manufacturers. Weight of semi-truck includes the combined weight of tractor and trailer, and has been taken from ORNL publication- 'Transportation Energy Data Book: Edition 31' (Davis et al., 2012).

ß The useful lives are based on the field experiences of the authors of this work. For tractors, useful life has been taken as 10,000 hr. For trucks, useful life has been taken as 800,000 km (i.e., 500,00 mi), as suggested by Berwick and Farooq (2003).

GHGE associated with the manufacture of the off-road farm machineries and on-road trucks is estimated using the total GHGE and energy consumed for the industrial processes in the U.S. in 2009. The total energy consumption for the industrial sector in 2009 was 28.2 quad (EIA, 2010) and the net GHGE was 2,240 Tg-CO_2e (4.9×10^{12} lb-CO_2e) (EIA, 2011). Thus, the GHGE associated with the manufacture of these equipment is estimated using the factor 75.3 g-CO_2e MJ^{-1} (i.e., 0.00018 lb-CO_2e BTU^{-1}) of energy consumed for their manufacture. In addition to these, life-cycle energy use and GHGE associated with the repair and maintenance of the off-road farm machineries and on-road trucks are estimated as 0.55 times of those associated with their manufacture (Fluck, 1985).

It has been considered that trucks in both the storage and biorefinery transports would be employed in other transportation activities when not involved in hauling biomass for biorefineries (i.e., during off-season for these activities of supply chain), thus, energy use and GHGE for manufacture and maintenance of trucks are allocated between their involvement in corn stover biomass supply chain and other off-seasonal transportation activities. Factors for allocating energy use and GHGE emissions for manufacture and maintenance of trucks used for storage and biorefinery transports are estimated as the ratio of truck use for these activities and the average annual use of trucks in U.S. Average annual miles travelled by Class 8 trucks in U.S. is taken as 107,450 km (i.e., 66,768 mi), as reported by FHA (2011). The annual use of trucks (km $year^{-1}$) for storage and biorefinery transports are estimated from their total travel distance in each trip and the annual truck trips by a single truck, details of the procedures for estimating both of these parameters are included in Chapter 2 of this dissertation.

The energy use and GHGE for off-road farm machineries and on-road trucks can also be evaluated using economic input-output life-cycle assessment methodology. EIO-LCA software developed by Green Design Institute of Carnegie Mellon University (CMU-GDI, 2013) can be used for this purpose. Details of this methodology have been explained in later section while estimating the life-cycle energy use and GHGE of consumables required for different processes of the supply chain.

3.3.4.2.2 Life-cycle energy use and greenhouse gas emissions associated with the operation of off-road farm machineries and on-road trucks

Well-to-wheel (WTW) life-cycle energy use and GHGE associated with the operation of different off-road farm machineries and on-road trucks are estimated as the direct energy use and GHGE due to diesel fuel consumption (i.e., pump-to-wheel (PTW) estimation) and the energy and GHGE embodied in diesel fuel during all the activities from its extraction, refining and final delivery to the oil pumps for sale (i.e., well-to-pump (WTP) estimation). All the farm machineries and trucks considered in this analysis operate on diesel fuel. WTW life-cycle energy and GHGE estimations for off-road machineries operations have been made based on their hourly fuel consumption rate (L hr^{-1}) (Table 3.1). Fuel consumption for biorefinery gate delivered stover (L std. Mg^{-1}) has been estimated using hourly fuel consumption information of machineries along with their productivities and annual usage hour, and annual feedstock requirement of the biorefinery. For trucks, WTW life-cycle fuel consumption and GHGE per unit distance travelled have been estimated using GREET Fleet Footprint Calculator (ANL, 2013), and are 0.37 L km^{-1} (0.16 gal mi^{-1}) and 1.19 kg-CO_2e km^{-1} (4.23 lb-CO_2e mi^{-1}), respectively. Truck fuel consumption and GHGE per unit distance estimate along with truck capacity and one-way travel distance information are used to estimate WTW fuel consumption (L std. Mg^{-1}) and GHGE (kg-CO_2e std. Mg^{-1}) for trucks. Thus, for trucks, this estimate directly yields WTW GHGE, and WTW energy usage for trucks has been estimated, in parts, as WTP and PTW. Procedures for estimating fuel consumption and productivities of farm machineries and trucks, and one-way travel distance for storage and biorefinery transports are thoroughly discussed in chapter 2 of this dissertation.

WTP energy usages for the operation of different farm machineries and trucks, and WTP GHGE for farm machineries only are estimated using their fuel consumption information and the factors used in GREET 1_2011 (2011) model. GREET 1_2011 (2011) has suggested the values for WTP energy use, and WTP carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions, respectively, as 0.204 MJ MJ^{-1} Diesel (203,702 BTU $mmBTU^{-1}$ Diesel), 15.9 g-CO_2 MJ^{-1} Diesel (16,785.9 g-CO_2 $mmBTU^{-1}$ Diesel), 0.12 g-CH_4 MJ^{-1} Diesel (128.4 g-CH_4 $mmBTU^{-1}$ Diesel) and 0.00021 g-N_2O MJ^{-1} Diesel (0.22 g-N_2O $mmBTU^{-1}$ Diesel). PTW energy usages for different machineries and trucks are then estimated using the energy content (HHV) of diesel fuel as 38.3 MJ L^{-1} (137,380 BTU gal^{-1}) (AFDC, 2013). In addition to this, PTW GHGE, including CO_2, CH_4 and N_2O, due to the operation of different agricultural machineries are estimated using the emission factors for the fuels reported by EPA (2008). EPA (2008) has reported the emission factors for diesel fuel combustion in agricultural equipment as 2682 g-CO_2 L^{-1} (22.38 lb-CO_2 gal^{-1}), 0.38 g-CH_4 L^{-1} (0.00317 lb-CH_4 gal^{-1}) and 0.07 g-N_2O L^{-1}

(0.00058 lb-N_2O gal^{-1}). CH_4 and N_2O emissions are expressed in terms of the mass of equivalent CO_2 emission (represented as kg-CO_2e) based on their 100-year global warming potentials (GWP). 100-year GWP for CH_4 and N_2O are, respectively, 25 and 298 times higher than that of CO_2 (Forster et al., 2007).

3.3.4.3 Life-cycle energy use and greenhouse gas emissions associated with consumables for different processes

Economic input-output life cycle assessment (EIO-LCA) model (CMU-GDI, 2013) has been used to estimate the life-cycle energy use and GHGE for the consumables. This model estimates the materials and energy resources required for, and the emissions resulting from various economic activities. String used for baling and tarp used for storage are two consumables used in corn stover biomass feedstock supply chain, and, among available options, both of these fit best within 'plastics packaging materials, film and sheet' economic sector of EIO-LCA software. Cost of these consumables for a million std. Mg of harvested corn stover feedstock, as estimated in chapter 2 of this dissertation, are used as economic inputs to EIO-LCA software. The costs are estimated in 2012$ in chapter 2 of this dissertation, so these are deflated to 2002$ as economic inputs to EIO-LCA software are in 2002$. Based on EIO-LCA model outputs, energy use shares of string and tarp, respectively, are 28 and 23.6 MJ std. Mg^{-1} (i.e., 24,264 and 20,283 BTU std. ton^{-1}) of harvested stover, and their GHGE shares, respectively, are 1.69 and 1.41 kg-CO_2e std. Mg^{-1} (i.e., 3.37 and 2.82 lb-CO_2e std. ton^{-1}) of harvested stover.

3.3.4.4 Life-cycle energy use and greenhouse gas emissions associated with nutrients removed from the field during stover collection

Life-cycle energy and GHGE are estimated for different nutrients, i.e., nitrogen (N), phosphorus (P) and potassium (K), removed from the field during stover collection. The amounts of P, in form of phosphorus pentoxide (P_2O_5), and K, in form of potassium oxide (K_2O), removed from the field during stover collection are estimated from the results of mineral ash analysis performed using ASTM Standard D3682 (2006) and the total ash content determined using ASTM Standard D3174 (2008). In addition to these, N removed is determined from the results of the ultimate analysis performed using ASTM Standard D5373 (2008).

Field test results suggest that, on an average, 2.5 kg-P_2O_5, 12.5 kg-K_2O and 7.7 kg-N are removed along with a dry and ash-free Mg of stover collected from the field. Next, energy and GHGE associated with the nutrients removal are estimated using the factors suggested by Kim and Dale (2004), which they estimated using the values published by Shapouri et al. (1995), Wang et al. (1999) and Wang (2000). Kim and Dale (2004) have suggested the values for energy use during the production of different nutrients as 70.6 MJ kg-N^{-1}, 19 MJ kg-$P_2O_5^{-1}$ and 9 MJ kg-K_2O^{-1}, and GHGE as 3.27 kg-CO_2e kg-N^{-1}, 1.34 kg-CO_2e kg-$P_2O_5^{-1}$ and 0.64 kg-CO_2e kg-K_2O^{-1}. Kim and Dale (2004) assumed the nitrogen fertilizer to consist of 69% ammonia and 31% urea, and have regarded the CO_2 generated in the ammonia plant as emission.

3.3.5 Monte Carlo simulation and sensitivity analysis

Monte Carlo simulation (500 iterations) has been performed to understand the impact of the variabilities of different input parameters on life-cycle energy use and GHGE from corn stover feedstock supply chain. Inputs for Monte Carlo simulations are based on production-scale field tests and possess normal probability distribution functions. Although this model is supplied with more than 100 inputs, only those tabulated with standard deviation in Table 3.1 are used to provide probability distribution functions for Monte Carlo simulation. Other inputs are supplied as a single value. All the results of this analysis are presented with 95% confidence interval (CI) on mean and 95% central range (CR) of the output data. In addition to these, histograms along with cumulative distribution function (CDF) graphs for different outputs discussed in the results section of this paper are included in the supporting material.

Sensitivity analysis was performed to determine the influence of 39 different input parameters (Table 3.3) on the life-cycle energy use and GHGE of corn stover biomass feedstock supply chain and its components. The pessimistic, most likely and optimistic values of different parameters were based on data from production-scale corn stover biomass supply chain research, and are consistent with those in the Chapter 2 of this dissertation. Additionally, different parameters are ranked based on the relative influence of their extreme values on overall EUR and GHGE of supply chain and its components. Sensitivity analysis energy use results in EUR and GHGE estimates for delivering a std. Mg of corn stover biomass to the biorefinery gate are discussed in this paper, and the sensitivity analysis results for different components of the supply chain are included as the supporting material. It should further be noted that for different supply chain components, sensitivity analysis are conducted to gauge the relative impacts of all 39 supply chain parameters (Table 3.3), however, only those influencing EUR and GHGE of different supply chain components are shown in the figures included as the supporting material. Both Monte Carlo simulation and sensitivity analysis are performed in macro-enabled spreadsheet. And, the necessary statistical analyses on output data to generate histograms and CDF graphs are performed in JMP software (SAS, 2013), and are included in the supporting material.

Table 3.3: Different parameters for the sensitivity analysis and range of their pessimistic, most likely and optimistic values

Parameters	*Units	*Ranges of Input Parameters		
		Pessimistic	Likely	Optimistic
Fuel Conversion Efficiency	L (clean Mg)$^{-1}$ (gal (clean ton)$^{-1}$)	292.1 (70)	329.6 (79)	367.2 (88)
Dry Matter Loss	%	10.0	7.5	5.0
Harvest Rate	std. Mg ha^{-1} (std. ton ac^{-1})	2.7 (1.2)	3.6 (1.6)	4.5 (2)
Ag Production in Iowa	% of Total Iowa area	80.0	86.0	90.0
Density of Corn	%	35.0	45.0	55.0
Producer Participation	%	20.0%	30.0	40.0
Bale Length	cm (in)	213.4 (84)	243.8 (96)	274.3 (108)
Bale Height	cm (in)	86.4 (34)	86.4 (34)	91.4 (36)
Bale Density	std. kg m^{-3} (std. lb ft^{-3})	144.2 (9)	166.8 (10.4)	192.2 (12)
Harvest Days	days	24	32	40
Windrower Working Hours	hr day^{-1}	7	8.5	10
Baler Working Hours	hr day^{-1}	7	8	9
Stacker Working Hours	hr day^{-1}	8	11	12
Windrower Fuel Consumption	L hr^{-1} (gal hr^{-1})	34.1 (9)	23.1 (6.1)	18.9 (5)
Baler Fuel Consumption	L hr^{-1} (gal hr^{-1})	37.9 (10)	27.6 (7.3)	18.9 (5)
Stacker Fuel Consumption	L hr^{-1} (gal hr^{-1})	28.8 (7.6)	17.4 (4.6)	13.6 (3.6)
Storage Transport: Loader Fuel	L hr^{-1} (gal hr^{-1})	24.6 (6.5)	20.8 (5.5)	17 (4.5)

Parameters	*Units	*Ranges of Input Parameters		
		Pessimistic	Likely	Optimistic
Consumption				
Biorefinery Transport: Loader Fuel Consumption	L hr^{-1} (gal hr^{-1})	24.6 (6.5)	20.8 (5.5)	17 (4.5)
Nitrogen Removed (Quantity)	kg-N (clean Mg)$^{-1}$ (lb-N (clean ton)$^{-1}$)	9 (18)	7.7 (15.4)	6.5 (13)
Potassium Removed (Quantity)	kg-K_2O (clean Mg)$^{-1}$ (lb-K_2O (clean ton)$^{-1}$)	15 (30)	12.5 (25)	10 (20)
Phosphorus Removed (Quantity)	kg-P_2O_5 (clean Mg)$^{-1}$ (lb-P_2O_5 (clean ton)$^{-1}$)	3.5 (7)	2.5 (5)	1.5 (3)
Windrower Field Efficiency	%	60	70	80
Windrower Transport Efficiency	%	75	85	95
Baler Field Efficiency	%	40	50	60
Baler Transport Efficiency	%	85	90	95
Baler Life (Planned Use)	bales	60,000	75,000	100,000
Stacker Theoretical Productivity	bales hr^{-1}	50	65	80
Stacker Field Efficiency	%	90	95	97
Stacker Transport Efficiency	%	85	90	95
Stacker Life (Planned Use)	bales	80,000	100,000	120,000
Storage Transport: Transport Window	days yr^{-1}	40	55	70
Storage Transport: Trucking Working Hours	hr day^{-1}	7	8	9
Storage Transport: Loader Life (Planned Use)	bales	80,000	100,000	120,000
Storage Stack Height	bales	4	6	6
Tarp Life	yr	1	2	2
Biorefinery Transport: Transportation Days	days yr^{-1}	200	280	300
Biorefinery Transport: Trucking Working Hours	hr day^{-1}	7	8	9
Biorefinery Transport: Loader Life (Planned Use)	bales	80,000	100,000	120,000
Number of Satellite Storage Facilities	Number	6	13	20

* Units and values in parentheses are in U.S. customary system of units

3.4 Results and Discussions

3.4.1 Life-cycle energy use and greenhouse gas emissions for corn stover biomass feedstock supply chain

Average life-cycle energy use and GHGE for feedstock supply chain to deliver corn stover biomass to the gate of a Midwest-based 114 MLPY (30 MGPY) biorefinery plant are estimated to be 1,502 (95% CI on mean: 1,490-1,513; 95% CR: 1,296-1,786) MJ std. Mg^{-1} (i.e., 1.291 (95% CI on mean: 1.281-1.301; 95% CR: 1.114-1.536) million BTU std. ton^{-1}) (Figure 3.1) and 95.2 (95% CI on mean: 94.1-96.3; 95% CR: 80.1-114.7) kg-CO_2e std. Mg^{-1} (i.e., 190.4 (95% CI on mean: 188.2-192.6; 95% CR: 160.2-229.4) lb-CO_2e std. ton^{-1}) (Figure 3.2), respectively. The variabilities in the overall life-cycle energy use and GHGE for feedstock supply chain are due to the variabilities in different supply chain parameters (Table 3.1). And, the parameters impacting energy use and GHGE for supply chain are identified and ranked using sensitivity analysis methodology, and are thoroughly discussed in a later section. Additionally, contributors to the energy use and GHGE of different supply chain components are included in the supporting material (Supporting Material, Figures S3.5-S3.11), and are briefly discussed in this section.

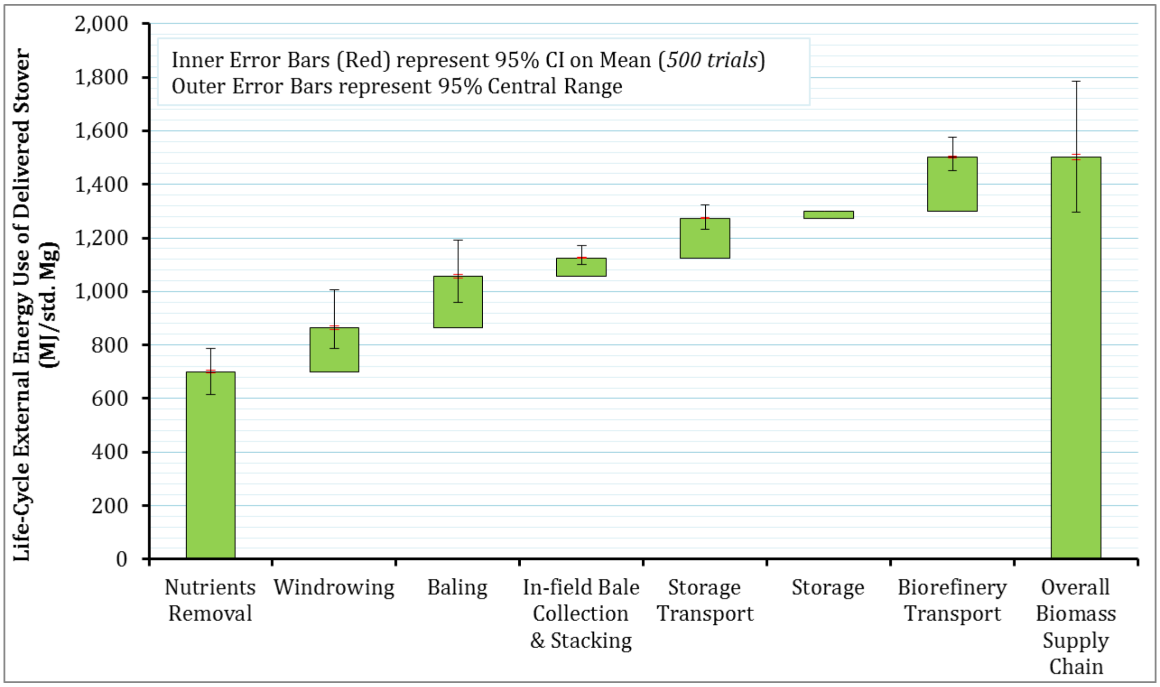

Figure 3.1: Life-cycle energy use for delivering corn stover biomass feedstock to the gate of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery

Nutrients removed during stover harvest, on average, are responsible for 47% of the life-cycle energy use and 38% of GHGE for the corn stover feedstock supply chain, and are the largest contributors. Average life-cycle energy use and GHGE associated with nutrients removed during stover harvest to supply corn stover to the biorefinery gate are estimated to be 701 (95% CR: 615-788) MJ std. Mg^{-1} and 37 (95% CR: 31-42) kg-CO_2e std. Mg^{-1} (i.e., 602 (95% CR: 529-677) thousands BTU std. ton^{-1} and 73 (95% CR: 62-84) lb-CO_2e std. ton^{-1}), respectively (Supporting Material, Figure S3.11). Out of the total life-cycle energy use and GHGE associated with nutrients, 68-77% is contributed by nitrogen alone, followed by around 16-22% by potassium. Sensitivity analysis conducted to gauge the influence of different supply chain parameters on life-cycle energy use and GHGE associated with nutrients removed from the field during stover harvest indicate that these metrics are the most sensitive to the quantity of nitrogen removed followed by the quantities of the other two nutrients (potassium and phosphorus) and DML (Supporting Material, Figure S3.18).

The findings of Nafziger (2011), as summarized by Jeschke and Heggenstaller (2012), show that with half of the stover removed from the field, nitrogen fertilizer requirement for corn production in continuous corn cropping practice with chisel plow and no-till systems decreased by around 10 and 50 kg-N ha^{-1} (i.e., 9 and 47 lb-N ac^{-1}), respectively. This reduction in nitrogen fertilizer requirement due to stover removal from the field will largely reduce the energy use and GHGE associated with nitrogen removal during stover collection, which is the largest contributor of these metrics of the supply chain. Nonetheless, energy expended associated with nutrients replenishment is significant and needs further research. Thus, effort should be directed toward exploring the ways to reduce the quantity of nutrients, mainly nitrogen, removed from the field during stover collection, and toward reducing the energy consumption during the manufacture and application of nutrients to the field.

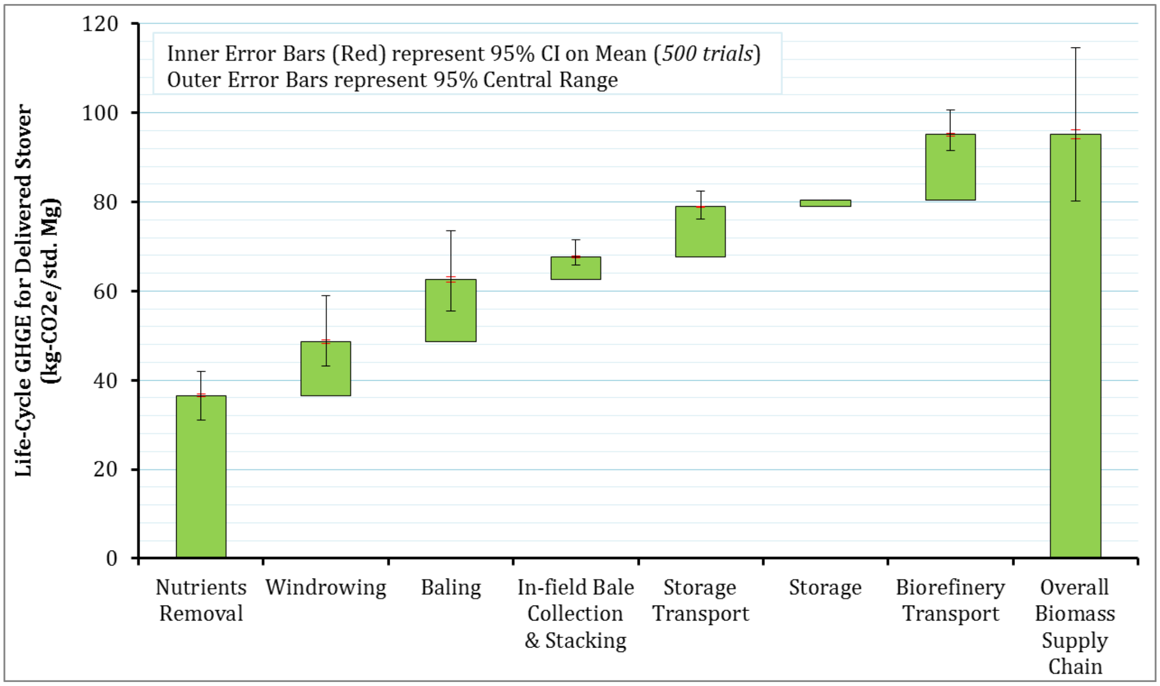

Figure 3.2: Life-cycle GHGE for delivering corn stover biomass feedstock to the gate of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery

Harvesting (combined windrowing and baling processes) and the transportation at the two ends of the supply chain (combined storage and biorefinery transports), both, on average, contribute to around 23.5% of the life-cycle energy use and around 27.5% of the life-cycle GHGE for the entire supply chain, and are the next major contributors following nutrients removed during stover harvest. In addition to these, stacking contributes to around 5% of the average overall energy use and GHGE for the supply chain. Average life-cycle energy use and GHGE for the windrowing process of the feedstock supply chain to deliver corn stover feedstock to the biorefinery gate are estimated to be 164 (95% CR: 87-306) MJ std. Mg^{-1} and 12.1 (95% CR: 6.6-22.3) kg-CO_2e std. Mg^{-1} (i.e., 141

(95% CR: 75-263) thousands BTU std. ton^{-1} and 24.1 (95% CR: 13.2-44.7) lb-CO_2e std. ton^{-1}), respectively (Supporting Material, Figure S3.5), and those for the baling process to be 192 (95% CR: 94-329) MJ std. Mg^{-1} and 14.0 (95% CR: 6.8-24.9) kg-CO_2e std. Mg^{-1} (i.e., 165 (95% CR: 81-283) thousands BTU std. ton^{-1} and 27.9 (95% CR: 13.6-49.7) lb-CO_2e std. ton^{-1}), respectively (Supporting Material, Figure S3.6). For the stacking process, average life-cycle energy use and GHGE are estimated to be 69 (95% CR: 43-116) MJ std. Mg^{-1} and 5.1 (95% CR: 3.3-8.8) kg-CO_2e std. Mg^{-1} (i.e., 59 (95% CR: 37-100) thousands BTU std. ton^{-1} and 10.2 (95% CR: 6.5-17.7) lb-CO_2e std. ton^{-1}), respectively (Supporting Material, Figure S3.7).

Around 62-70% of the overall energy use and GHGE for harvesting and stacking processes are due to the operation of the associated machineries. The sensitivity analysis results indicate that energy use and GHGE for all three processes (windrowing, baling and stacking) are the most sensitive to the quantities of fuel consumed for their operation. Additionally, energy use and GHGE for these supply chain components are sensitive to harvest rate (windrowing and baling only), productivities, efficiencies (field and transport), working durations, fuel conversion efficiency, DML, and bale density, length and height (baling and stacking only) (Supporting Material, Figures S3.12-S3.14). This reflects the need for the future research to be directed toward optimizing the performances of different farm machineries to minimize their fuel consumptions and to maximize their productivities. Enhancing fuel efficiencies of machineries is usually difficult mainly due to the need to improve/modify the engines; however, their productivities can be practically enhanced in the field level in different ways as suggested in Chapter 2 of this dissertation. Additional research can focus toward innovation in stover harvesting machineries through combining different processes in the same unit. An example for this is single-pass systems for simultaneous grain and stover harvesting.

Average life-cycle energy use and GHGE for the storage transport process are estimated to be 149 (95% CR: 108-198) MJ std. Mg^{-1} and 11.2 (95% CR: 8.4-14.7) kg-CO_2e std. Mg^{-1} (i.e., 128 (95% CR: 93-170) thousands BTU and 22.4 (95% CR: 16.8-29.4 lb-CO_2e), respectively (Supporting Material, Figure S3.8), and those for the biorefinery transport process are estimated to be 202 (95% CR: 153-276) MJ std. Mg^{-1} and 14.7 (95% CR: 11.2-20.2) kg-CO_2e std. Mg^{-1} (i.e., 174 (95% CR: 132-237) thousands BTU std. ton^{-1} and 29.5 (95% CR: 22.4-40.4) lb-CO_2e std. ton^{-1}), respectively (Supporting Material, Figure S3.10). Despite using same equipment and hauling an identical quantity of corn stover bales, average energy use and GHGE for biorefinery transportation are higher than those for the storage transportation, mainly due to longer travel distance for biorefinery transport. Shares of storage on both energy use and GHGE for the overall supply chain are the least, and, on an average, are less than 2%. Average life-cycle energy use and GHGE for storing corn stover biomass with tarp cover are estimated to be 26 MJ std. Mg^{-1} and 1.5 kg-CO_2e std. Mg^{-1} (i.e., 22 thousands BTU std. ton^{-1} and 3.1 lb-CO_2e std. ton^{-1}), respectively (Supporting Material, Figure S3.9), and are contributed entirely due to the production and distribution of tarp.

Average life-cycle energy use and GHGE shares of loaders for storage and biorefinery transports, respectively, are around 75 and 55%. The average energy use and GHGE shares for loaders are higher in storage transportation compared to that in biorefinery transportation, primarily, due to the need of a greater number of loaders to support transportation activities in shorter operating duration. Additionally, travel distance for trucks in storage transport is shorter than in biorefinery transportation (Chapter 2 of this dissertation), thus, truck productivity is higher in storage transport; and, loaders, having the same productivities in both the transportation activities, need to handle identical number of bales in shorter duration in storage transport requiring higher number of loaders. 57-67% of the life-cycle energy use and GHGE for loaders used for both the storage and biorefinery transports are due to their operation, which follows the same discussion as that for stackers. For trucks in both the transportation activities, operation share around 95% of the overall energy use and GHGE. Manufacture and maintenance shares of trucks are minimal due to their off-seasonal use in activities other than hauling stover for the biorefineries purpose, as discussed earlier. Moreover, this analysis estimates the overall energy use and GHGE associated with the manufacture and maintenance of the trucks regardless of the purpose these are used, but energy use and GHGE associated with operation is entirely for supplying feedstock to the biorefinery gate, thus, use-based allocation factors are applicable only to the maintenance and manufacture of the trucks. Allocation factors for energy use and GHGE associated with the maintenance and manufacture of trucks in storage and biorefinery transports are 9.1 (95% CR: 7.7-11.6) % and 74.4 (95% CR: 68.4-79.6) %, respectively. Despite higher allocation factor for energy use and GHGE associated with manufacture and maintenance of trucks in biorefinery transport, operation share is identical to that in storage transport due to longer travel distances as well as due to negligible contribution of trucks manufacture and maintenance compared to their operation.

Sensitivity analyses results (Supporting Material, Figures S3.15 and S3.17) indicate that energy use and GHGE for both the storage and biorefinery transports are highly sensitive to bale density, which impacts the overall bale supply requirement resulting in the change in overall truck trips requirement. In addition to bale density, energy use and GHGE for both the storage and biorefinery transports are sensitive to bale length and bale height creating same impact as bale density; working durations impacting the overall number of equipment requirement; producer participation, density of land in corn, agricultural production and harvest rate impacting the overall supply area that results in the change in overall travel distance for the trucks; fuel conversion efficiency and DML impacting the overall feedstock supply requirements; and the other supply chain parameters, as number of satellite storage facilities, loader fuel consumption and useful life.

3.4.2 Life-cycle energy-use ratio (EUR) for corn stover biomass feedstock supply chain

EUR is the ratio of the external energy used by the feedstock supply chain to deliver stover to the biorefinery gate to produce cellulosic ethanol and the overall energy contained in the produced ethanol. Average EUR for the stover supply chain is estimated to be 21.0 (95% CR: 17.9-25.6) % (Figure 3.3), which indicates that the average energy expended for feedstock supply chain to deliver corn stover biomass to the biorefinery gate is around 21% of the energy content of the produced cellulosic ethanol. Average EUR for nutrients removed during stover harvest is 9.8% and is the highest among different supply chain components. For harvesting, EUR is around 5.0%, with that for baling being higher than that for windrowing. For transportation at the two ends of the supply chain, EUR is 4.9%, with that for biorefinery transport being higher than that for storage transport, mainly, due to longer travel distance for the former.

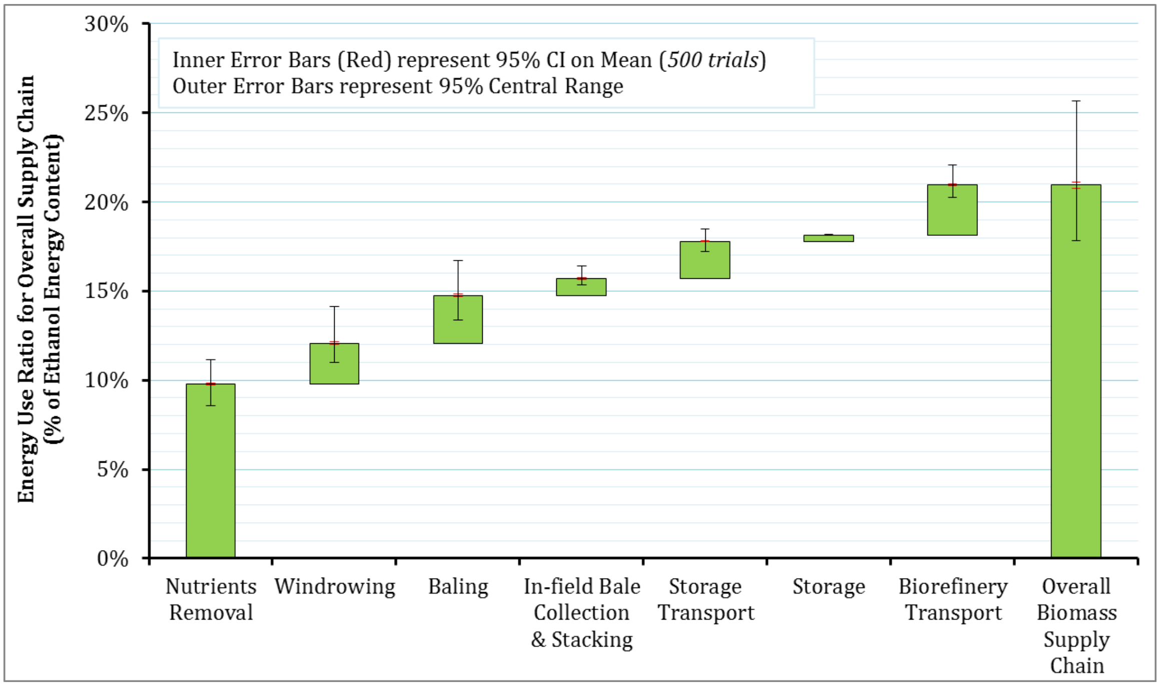

Figure 3.3: Life-cycle EUR for delivering corn stover biomass feedstock to the gate of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery

In addition to the energy use and GHGE for biorefinery gate delivered stover and EUR estimates, average annual energy use for corn stover feedstock supply chain of a 114 MLPY (30 MGPY) Midwest-based cellulosic biorefinery is estimated to be 561 (95% CR: 478-686) million MJ (i.e., 531 (95% CR: 453-650) billion BTU) (Supporting Material, Figure S3.1) and GHGE to be 35.8 (95% CR: 29.5-43.9) million kg-CO_2e (i.e., 78.9 (95% CR: 65.0-96.7) million lb-CO_2e) (Supporting Material, Figure S3.2); and for delivering corn stover to the biorefinery gate to produce a unit volume of cellulosic ethanol, energy use and GHGE are estimated to be 4.94 (95% CR: 4.21-6.04) MJ L^{-1} (i.e., 17.7 (95% CR: 15.1-21.7) thousand BTU gal^{-1}) (Supporting Material, Figure S3.3) and 0.32 (95% CR: 0.26-0.39) kg-CO_2e L^{-1} (i.e., 2.6 (95% CR: 2.2-3.2) lb-CO_2e gal^{-1}) (Supporting Material, Figure S3.4), respectively. Venkatesh et al. (2011) has reported the overall life-cycle GHGE for gasoline, including crude oil extraction, transportation to refineries, refining, transportation of gasoline to pumps and combustion operations as 89.2 g-CO_2e MJ^{-1}. Taking HHV of ethanol as 23.6 MJ L^{-1} (AFDC, 2013), average GHGE for the corn stover supply chain is around 15% of the life-cycle emissions for gasoline. It should be noted that the GHGE estimates in this study doesn't include the biofuels production, distribution and utilization phases. Furthermore, to meet the EISA (2007) target to reduce the GHGE from biofuels at least by 60% than that from gasoline, the proportion of stover supply chain on the target GHGE level mandated by EISA is around 38%, leaving around 62% for the other activities related to biofuels production, distribution and utilization. Thus, for making federal biofuels target a reality, there is need to further improve the performances of the overall supply chain to reduce the overall GHGE from this component of the supply, and some of the strategies to achieve emissions reduction for supply chain as well as the potentially achievable reductions are discussed in a later section.

3.4.3 Sensitivity analysis of life-cycle energy-use ratio and greenhouse gas emissions of the corn stover biomass feedstock supply chain

Ranges to which EUR and GHGE for the feedstock supply chain of a Midwest-based 114 MLPY (30 MGPY) biorefinery plant varies depending upon the pessimistic, most likely and optimistic values of 39 different inputs parameters

(Table 3.3) and their rankings based on their relative influence on EUR and GHGE are presented in Figures 3.4 and 3.5. Most likely life-cycle EUR and GHGE for the overall corn stover feedstock supply chain (estimated deterministically at the most likely values of different supply chain parameters (Table 3.3), and should not be confused with previously discussed stochastic estimates using Monte-Carlo simulation method) are 20.5% and 92.1 kg-CO_2e std. Mg^{-1} (i.e., 184.3 lb-CO_2e std. ton^{-1}). In the optimistic operating condition, combined effect of all the supply chain parameters considered in this study can decrease overall EUR and GHGE for supply chain, respectively, by 11.5% points to 9% and by 47.0 kg-CO_2e std. Mg^{-1} (i.e., 94.0 lb-CO_2e std. ton^{-1}) to 45.1 kg-CO_2e std. Mg^{-1} (i.e., 90.3 lb-CO_2e std. ton^{-1}). In pessimistic working conditions, overall EUR and GHGE for the supply chain can increase, respectively, by around 12.7% points to around 33.2% and by around 49.5 kg-CO_2e std. Mg^{-1} (i.e., 99 lb-CO_2e std. ton^{-1}) to around 141.6 kg-CO_2e std. Mg^{-1} (i.e., 283.2 lb-CO_2e std. ton^{-1}).

Among different parameters considered for sensitivity analysis, EUR has been identified to be the most sensitive to fuel conversion efficiency as higher ethanol yield per unit mass of stover reduces the overall feedstock quantity requirement of the biorefinery. The next six most sensitive supply chain parameters to EUR are quantity of nitrogen removed from the field during stover harvest, followed by bale density, bale length, harvest rate, DML and baler field efficiency (Figure 3.4). The same six parameters are identified to be the top six most sensitive parameters on overall GHGE for the supply chain; however, bale density leads their ranking, followed by bale length, harvest rate, quantity of nitrogen removed, baler field efficiency and DML (Figure 3.5). In the optimistic and pessimistic operating conditions, combined effect of these 6 parameters can contribute, respectively, to around 40% decrease as well as increase of the overall EUR and to around 45% decrease and 48% increase of the overall GHGE attained at optimistic and pessimistic values of all supply chain parameters considered in this study.

EUR and GHGE due to nitrogen removed from the field during stover harvest and baler field efficiency, despite having huge influence in overall EUR and GHGE of the supply chain, affects only EUR and GHGE due to nutrients removed from the field and baling process, respectively (Supporting Material, Figures S3.13 and S3.18). However, bale density, bale length, harvest rate and DML impacts EUR and GHGE for almost all the components of the supply chain (Supporting Material, Figures S3.12-S3.18), and, thus have global impact on the supply chain. Any improvements in these supply chain parameters can impact the energy use and GHGE for different supply chain components.

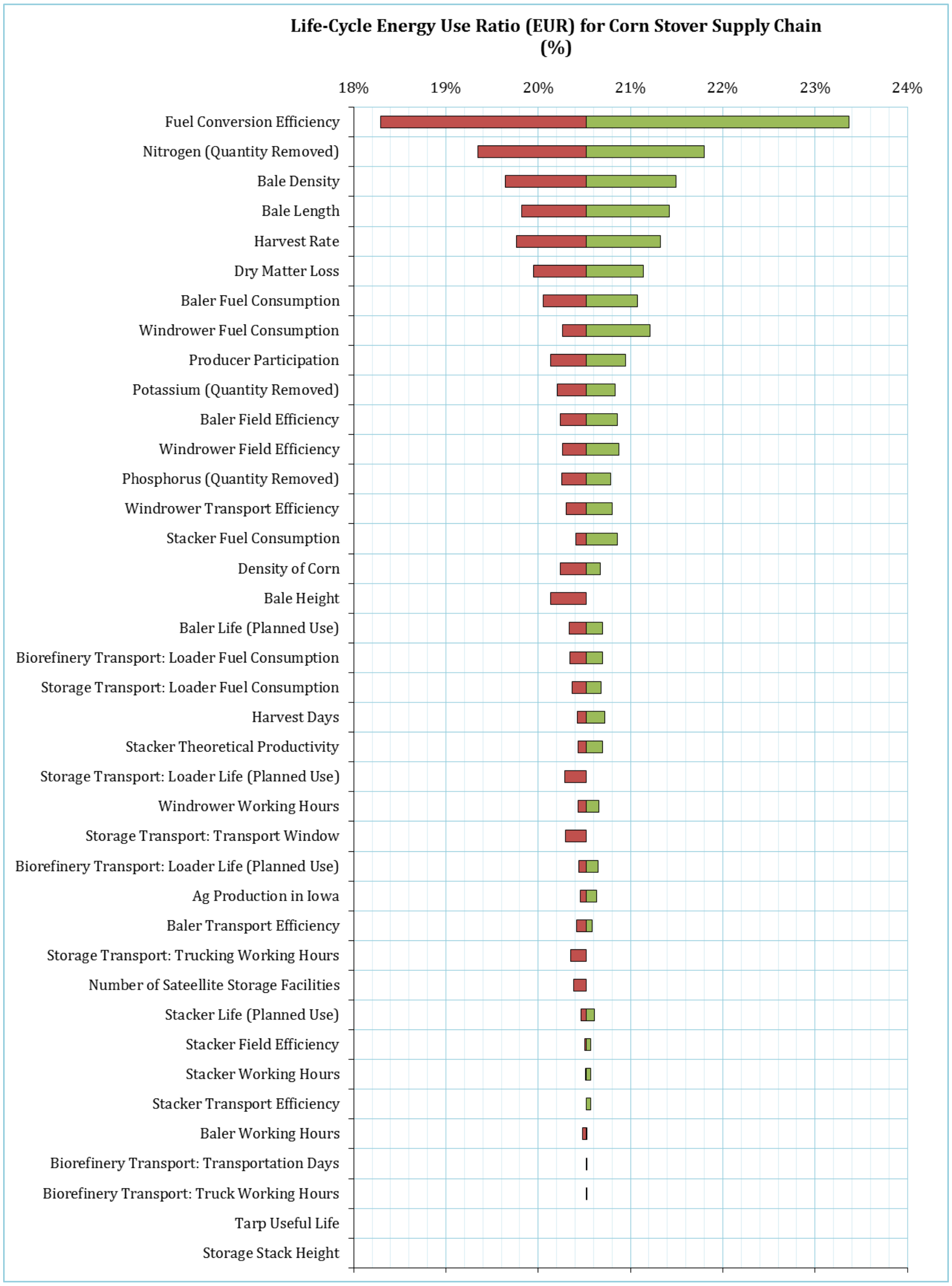

Figure 3.4: Sensitivity of life-cycle EUR for delivering corn stover biomass feedstock to the gate of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery plant on the pessimistic, most likely and optimistic values of 39 different supply chain system parameters (Table 3.3)

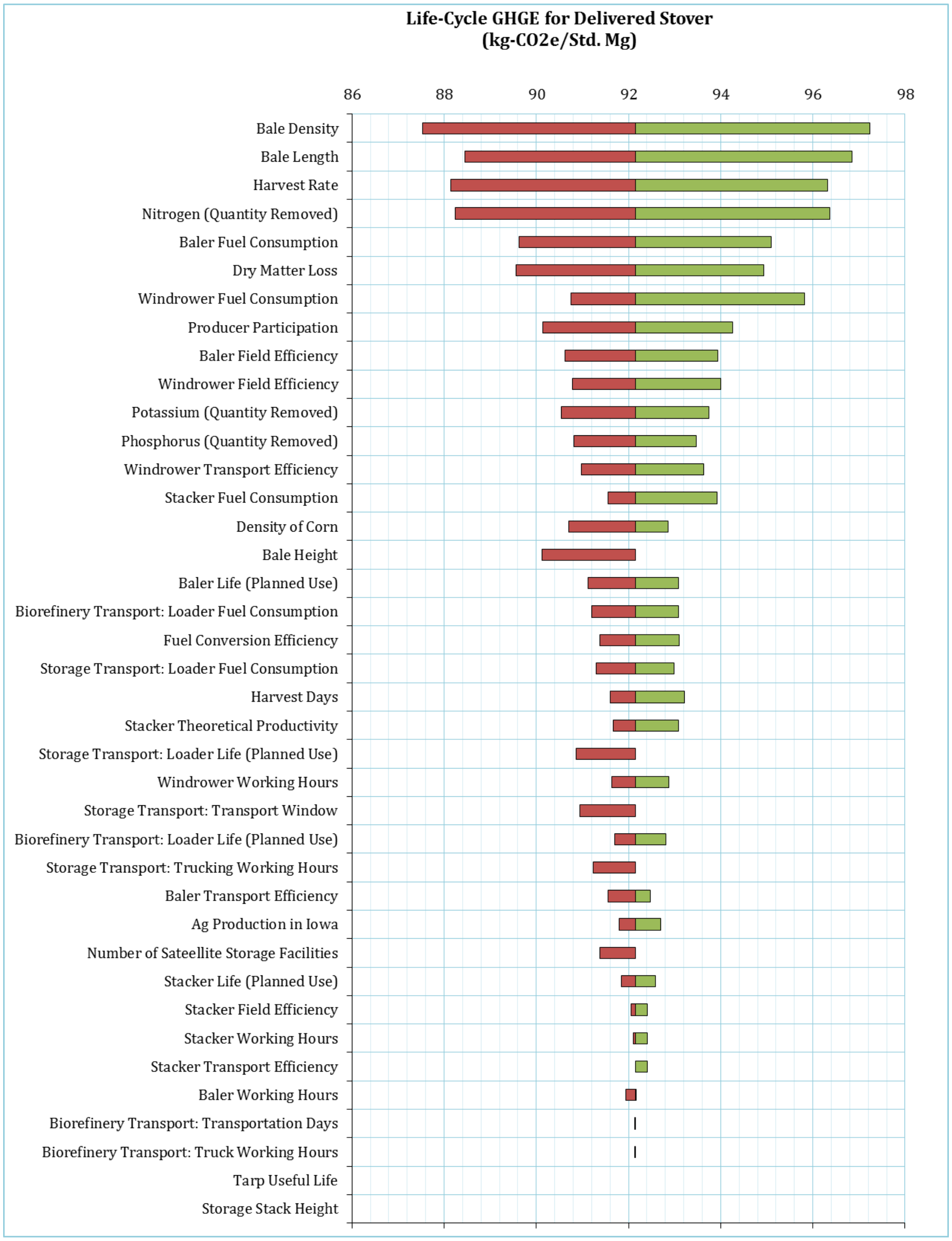

Figure 3.5: Sensitivity of life-cycle GHGE for delivering corn stover biomass feedstock to the gate of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery plant on the pessimistic, most likely and optimistic values of 39 different supply chain system parameters (Table 3.3)

3.4.4 Comparison of energy use and greenhouse gas emissions for corn stover biomass feedstock supply chain from this study with selected published literatures

Table 3.4 summarizes the life-cycle energy use and GHGE for different components of corn stover biomass feedstock supply chain as estimated in this study and reported by the other researchers (GREET 1, 2011; Morey et al., 2010; Sokhansanj and Hess, 2009). The life-cycle energy use and GHGE for corn stover feedstock supply chain estimated in this study is comparative to that obtained from GREET 1 (2011). Some variations in the results obtained from this study and those from GREET 1 (2011) are mainly due to the data sources. As discussed earlier GREET incorporates data from multiple sources, and, thus is more generalized; however, this study uses data obtained from the field experiments conducted in Iowa, and, thus the results are specific to the Midwest. Life-cycle energy use and GHGE for harvesting and stacking processes reported by Sokhansanj and Hess (2009) and Morey et al. (2010) (considering storage transport in Table 3.4 as stacking for Morey et al. (2010)) are around 35-75% that of those estimated in this study, which is primarily due to discrepancies in data. Sokhansanj and Hess (2009) and Morey et al. (2010) uses data obtained from small scale operations, and fails to capture the scale to which supply chain for biorefineries would execute. Life-cycle energy use and GHGE associated with nutrients removed during stover harvest estimated using GREET 1 (2011) and by Morey et al. (2010) are within 20% of those reported in this study. Thus, for the consistency in life-cycle energy and GHGE estimates, uniformity in data collection methodology as well as homogenization of functional units and system boundaries are essential.

†, # Table 3.4: Summary of energy use and GHGE for corn stover biomass feedstock supply chain from different sources, including this study

Supply Chain Components	* GREET 1, Version 2011.0.0 (2011)		^ Morey et al. (2010)		Δ Sokhansanj and Hess (2009)		This Study	
	Energy Use	GHGE	Energy Use	GHGE	Energy Use	GHGE	Energy Use	GHGE
#Windrowing	447.0	35.5	49.6	3.8	83.0	6.5	164.2	12.1
Baling	-	-	40.4	3.1	133.0	10.4	191.8	14.0
Stacking	-	-	NA	NA	83.0	6.5	68.5	5.1
Storage transport	208.1	16.2	76.2	5.8	NA	NA	149.3	11.2
Storage (with tarp cover)	NA	NA	35.9	2.6	12.0	0.9	25.5	1.5
Biorefinery transport	-	-	NA	NA	NA	NA	201.8	14.7
Nutrients (N, P and K) removal	567.7	44.9	485.6	36.5	NA	NA	700.6	36.6
¥ Overall supply chain	1,222.8	96.6	-	-	-	-	1,501.7	95.2

† Energy use and GHGE values from different studies are adjusted to report the results in the units of MJ Mg^{-1} and kg-CO_2eq. Mg^{-1}, respectively. Although this study estimates energy use and GHGE for std. Mg (weight at 0% moisture and 8% ash contents), results for other studies are reported in dry basis as ash content information are not provided.

'NA' refers to 'Not estimated in the cited study'; and '-' refers to have been included with energy use and GHGE of the other components

* Details are provided in Wu et al. (2006), which is the first published report after the incorporation of corn stover-based ethanol production in GREET model. This estimation considers large round bales, harvest rate of 4.5 Mg/ha (i.e., 2 ton/ac); and, the reported values for transportation are based on one-way travel distance of 61.5 km (default in GREET). Additionally, reported value within 'windrowing' row is the total of windrowing, baling and stacking operations comparable to this study. Furthermore, these estimates are based on a single transportation event between

field-edge to the biorefinery gate. GREET does not estimate life-cycle energy use and GHGE associated with the storage process.

^ Morey et al. (2010) uses three-pass system in which shredding is followed by raking and round baling. Life-cycle energy use and GHGE for stacking process has not been separately estimated. Instead, they estimated life-cycle energy use and GHGE for the in-field bale collection and moving to the storage location for an average round-trip distance of 5.6 km, which has been considered identical to 'storage transport' in this study, and 'stacking' has not been included. Additionally, they considered densifying stover bales using grinder and roll-pressing before transporting to the plant, thus, this component doesn't directly compare with the system boundary of the present study and has not been reported after storage. They considered storing round, net-wrapped bales uncovered at the local storage sites (without any infrastructure) for durations from 1 to 11 months, and have considered the DML of 5%.

∆ Estimates of Sokhansanj and Hess (2009) are based on Integrated Biomass Supply Analysis and Logistics (IBSAL) model. Details of IBSAL model can be found at Sokhansanj et al. (2006).

¥ Life-cycle energy use and GHGE for the overall supply chain are reported only for GREET estimates as GREET's system boundary is comparable to that of the present study.

3.5 Potential strategies to reduce life-cycle energy use and GHGE for corn stover biomass feedstock supply chain

Three potential strategies for reducing the cost of stover supply chain as discussed in Chapter 2 of this dissertation also have the potentials to reduce its life-cycle energy use and GHGE. These were thoroughly discussed in the Chapter 2 of this dissertation and will not be discussed in much depth in this paper; however, the impacts of improvements in the main parameters of the supply chain on its life-cycle energy use and GHGE under three different strategies will be discussed here. Furthermore, based on the arguments presented in Chapter 2 of this dissertation, impacts of the improvements in different parameters on the life-cycle energy use and GHGE of the supply chain will exclude those for nutrients, thus, the life-cycle energy use and GHGE for the entire supply chain in this section will refer to the combined life-cycle energy use and GHGE for all the supply chain components excluding nutrients, unless otherwise mentioned. The most likely life-cycle energy use, EUR and GHGE for the entire supply chain, estimated using the 'most likely' values of parameters in current context (Table 3.3), are 766 MJ std. Mg^{-1} (658 thousand BTU std. ton^{-1}), 10.7% and 55.8 kg-CO_2e std. Mg^{-1} (111.6 lb-CO_2e std. ton^{-1}), respectively, and the impacts of the potential improvements in different supply chain parameters on EUR and GHGE are included in Tables 3.5 and 3.6.

The first strategy to reduce the overall supply chain cost was to reduce the stover feedstock supply area, which can either be reduced by increasing the density of corn stover availability in the vicinity of the biorefinery plant by increasing producers' participation in harvesting stover or by increasing the harvest rate of stover in the corn fields, or by reducing the overall stover harvest requirements to meet biorefinery demand which could be done by reducing the overall DML for the supply chain. The combined impact of increasing producers' participation from the current baseline 30 to 40%, harvest rate from 3.6 Mg ha^{-1} (1.6 ton ac^{-1}) to 4.5 Mg ha^{-1} (2.0 ton ac^{-1}), and reducing supply chain DML from 7.5 to 5% can reduce the baseline life-cycle EUR and GHGE for the entire supply chain by 1.5% points and 7.6 kg-CO_2e std. Mg^{-1} (15.3 lb-CO_2e std. ton^{-1}), respectively, to 9.2% and 48.2 kg-CO_2e std. Mg^{-1} (96.3 lb-CO_2e std. ton^{-1}) (Tables 3.5 and 3.6). Producers' participation impacts the transportation activities by changing the travel distances between field-edge, central storage facilities and the biorefinery plant, and harvest rate impacts harvesting and transportation activities. DML impacts all the supply chain components, as change in DML reduces the overall requirement of biomass quantity to be harvested, and, thus, changes the material flow quantity through different supply chain components.

The next strategy for reducing the overall supply chain cost, as discussed in the Chapter 2 of this dissertation, was to reduce the overall bale supply quantity requirement of a biorefinery that can be achieved by increasing the density or length or height of the individual bales. The combined impact of increasing bale density from 167 std. kg m^{-3} (10.4 std. lb ft^{-3}) to 192 std. kg m^{-3} (12 std. lb ft^{-3}), bale length from 244 cm (96-in) to 274 cm (108-in), and bale height from 86 cm (34-in) to 91 cm (36-in) can reduce the life-cycle EUR and GHGE for the entire supply chain by 2% points and 10.3 kg-CO_2e std. Mg^{-1} (20.7 lb-CO_2e std. ton^{-1}), respectively (Tables 3.5 and 3.6). Reducing bale supply requirement impact all the post windrowing processes of the supply chain due to the direct reduction in need to handle the bales passing through different components.

Table 3.5: Summary of potential reductions in the overall energy use for the corn stover biomass supply chain depending upon the strategic improvements in some major supply chain parameters

Parameters	*Units	*Values of Parameters		Overall Supply Chain	Windrowing	Baling	Stacking	Storage Transport	Storage	Biorefinery Transport	*Achieved Overall Supply Chain Energy Use
		Most Likely	Target								
Baseline Energy Use	MJ-std. Mg^{-1} (BTU-std. ton^{-1})	All	-	766 (658,402)	148 (127,355)	181 (156,024)	60 (51,824)	152 (130,998)	26 (21,928)	198 (170,273)	766 (658,402)
Baseline EUR	%	All	-	10.7	2.1	2.5	0.8	2.1	0.4	2.8	10.7
Overall Energy Savings	%	-	All	4.4	1	0.8	0.3	0.9	0	1.4	
Final EUR	%	-	All	6.3	1.1	1.7	0.6	1.2	0.3	1.4	6.3
Parameter-wise Breakdown for Overall Cost Savings				Energy Savings (in terms of EUR) for Corn Stover Biomass Feedstock Supply Chain and its Components excluding Nutrients (%)							
Producers' Participation	%	30	40	0.4	-	-	-	0.13	-	0.26	10.3
Harvest Rate	std. Mg ha^{-1} (std. ton ac^{-1})	3.6 (1.6)	4.5 (2.0)	0.8	0.31	0.14	-	0.1	-	0.21	9.6
Dry Matter Loss (DML)	%	7.5	5	0.3	0.05	0.07	0.02	0.07	0.01	0.1	9.2
Bale Density	std. kg m^{-3} (std. lb ft^{-3})	166.8 (10.4)	192.2 (12.0)	0.9	-	0.11	0.12	0.28	-	0.37	8.4
Bale Length	cm (in)	243.8 (96.0)	274.3 (108.0)	0.7	-	0.06	0.1	0.24	-	0.31	7.7
Bale Height	cm (in)	86.4 (34.0)	91.4 (36.0)	0.4	-	0.06	0.05	0.12	-	0.16	7.3
Windrower Field Efficiency	%	70	80	0.3	0.26	-	-	-	-	-	7.0
Windrower Transport Efficiency	%	85	95	0.2	0.22	-	-	-	-	-	6.8
Baler Field Efficiency	%	50	60	0.3	-	0.29	-	-	-	-	6.5
Baler Transport Efficiency	%	90	95	0.1	-	0.11	-	-	-	-	6.4
Harvest Days	days yr^{-1}	32.0	40.0	0.1	0.12	-0.02	-	-	-	-	6.3

* Units and values in parentheses are in U.S. customary units

Table 3.6: Summary of potential reductions in the overall GHGE for the corn stover biomass supply chain depending upon the strategic improvements in some major supply chain parameters

Parameters	*Units	*Values of Parameters		Overall Supply Chain	Windrowing	Baling	Stacking	Storage Transport	Storage	Biorefinery Transport	*Achieved Overall Supply Chain GHGE
		Most Likely	Target								
Baseline GHGE	(kg-CO_2e std. Mg^{-1} (lb-CO_2e std. ton^{-1}))	All	-	55.8 (111.6)	11.1 (22.2)	13.1 (26.2)	4.5 (9.0)	11.2 (22.4)	1.5 (3.1)	14.3 (28.7)	55.8 (111.6)
Overall GHGE Savings	(kg-CO_2e std. Mg^{-1} (lb-CO_2e std. ton^{-1}))	-	All	23.4 (46.9)	5.6 (11.3)	4.3 (8.6)	1.3 (2.7)	4.9 (9.8)	0.0 (0.1)	7.2 (14.4)	
Final GHGE	(kg-CO_2e std. Mg^{-1} (lb-CO_2e std. ton^{-1}))	-	All	32.3 (64.7)	5.5 (10.9)	8.8 (17.6)	3.2 (6.3)	6.3 (12.6)	1.5 (3.0)	7.1 (14.3)	32.3 (64.7)
Parameter-wise Breakdown for Overall Cost Savings				*GHGE Savings for Corn Stover Biomass Feedstock Supply Chain and its Components excluding Nutrients (kg-CO_2e std. Mg^{-1} (lb-CO_2e std. ton^{-1}))							
Producers' Participation	%	30	40	2.0 (4.0)	-	-	-	0.7 (1.4)	-	1.3 (2.6)	53.8 (107.6)
Harvest Rate	std. Mg ha^{-1} (std. ton ac^{-1})	3.6 (1.6)	4.5 (2.0)	4.0 (8.0)	1.7 (3.3)	0.7 (1.5)	-	0.5 (1.1)	-	1.0 (2.1)	49.8 (99.6)
Dry Matter Loss (DML)	%	7.5	5	1.6 (3.3)	0.3 (0.6)	0.3 (0.7)	0.1 (0.2)	0.4 (0.7)	0.0 (0.1)	0.5 (1.0)	48.2 (96.3)
Bale Density	std. kg m^{-3} (std. lb ft^{-3})	166.8 (10.4)	192.2 (12.0)	4.6 (9.2)	-	0.6 (1.2)	0.6 (1.2)	1.5 (3.0)	-	1.9 (3.8)	43.5 (87.1)
Bale Length	cm (in)	243.8 (96.0)	274.3 (108.0)	3.7 (7.4)	-	0.3 (0.7)	0.5 (1.0)	1.2 (2.5)	-	1.6 (3.2)	39.8 (79.7)
Bale Height	cm (in)	86.4 (34.0)	91.4 (36.0)	2.0 (4.0)	-	0.3 (0.7)	0.3 (0.5)	0.6 (1.2)	-	0.8 (1.6)	37.8 (75.7)
Windrower Field Efficiency	%	70	80	1.4 (2.7)	1.4 (2.7)	-	-	-	-	-	36.5 (72.9)
Windrower Transport Efficiency	%	85	95	1.2 (2.3)	1.2 (2.3)	-	-	-	-	-	35.3 (70.6)
Baler Field Efficiency	%	50	60	1.5 (3.0)	-	1.5 (3.0)	-	-	-	-	33.8 (67.6)
Baler Transport Efficiency	%	90	95	0.6 (1.2)	-	0.6 (1.2)	-	-	-	-	33.2 (66.4)
Harvest Days	days yr^{-1}	32.0	40.0	0.5 (1.1)	0.7 (1.3)	-0.1 (-0.2)	-	-	-	-	32.6 (65.3)

* Units and values in parentheses are in U.S. customary units

The final strategy discussed in Chapter 2 of this dissertation was to reduce the quantities of in-field farm machineries that can be practically achieved by improving their productivities or increasing the working durations. Productivities of farm machineries can be improved by increasing the harvest rate, and their field and transport efficiencies. Impact of harvest rate has already been discussed under the strategy to reduce the overall supply area requirement. Unlike for cost reduction strategies (Chapter 2 of this dissertation), impacts of stacker transportation efficiency, and windrower and baler working hours in life-cycle energy and GHGE has not been evaluated due to their negligible sensitivities in these metrics (Figures 3.4 and 3.5). The combined impact of increasing field and transport efficiencies of windrowers and balers from current baseline values of 70, 50, 85and 90%, respectively, to 80, 60, 95 and 95%, and harvest window from 32 to 40 days yr^{-1} can reduce the life-cycle EUR and GHGE for the entire supply chain by 1% points and 5.2 kg-CO_2e std. Mg^{-1} (10.4 lb-CO_2e std. ton^{-1}), respectively (Tables 3.5 and 3.6). Unlike other two strategies, improvement in the performances in parameters under this strategy impacts their respective operations, and reduces the life-cycle energy and GHGE by reducing the time requirement to complete their respective tasks. Operating duration has minimal impact as extended duration allows for more time but doesn't change the performances of the machineries, thus, despite reducing the quantities of equipment requirement which has direct impact on the supply chain cost, doesn't necessary create huge impact on life-cycle energy use and GHGE. More specifically, extended duration primarily impacts the life-cycle energy and GHGE related to the manufacture and maintenance of farm machineries, which contributes only to around 25-30% of the life-cycle energy and GHGE for the windrowing and baling operations.

Effective implementation of the three strategies discussed above can reduce the life-cycle EUR and GHGE for the entire supply chain by 4.4% points and 23.4 kg-CO_2e std. Mg^{-1} (46.9 lb-CO_2e std. ton^{-1}), respectively, to 6.3% and 32.3 kg-CO_2e std. Mg^{-1} (64.7 lb-CO_2e std. ton^{-1}) (Tables 3.5 and 3.6). Upon the successful implementation of these three strategies, average GHGE for the corn stover supply chain, including nutrients, is around 11.5% of the life-cycle emissions for gasoline (i.e., around 3.5% points reduction from the current level, as discussed in the previous section); and, the proportion of stover supply chain out of the target GHGE level mandated by EISA (2007) can reduce to around 28.5% (i.e., around 10% less than the current level, as discussed in the previous section).

It is further essential to compare the life-cycle energy use and GHGE outcomes with cost results, and prioritize the sectors that needs attention. Figure 3.6 shows the contributions of different components of the supply chain on its overall cost (obtained using results from the Chapter 2 of this dissertation) and life-cycle energy use and GHGE. In cost perspective, average costs of the two activities related to corn stover collection (i.e., windrowing and baling) and the two activities associated with transportation (i.e., storage and biorefinery transport), each share around 30% of the overall supply chain cost followed by 22% for nutrients; and, in life-cycle energy use and GHGE perspective, nutrients alone contribute to 38-47%

of that for the overall supply chain, followed by around 23-28% for each harvesting and transportation activities. Thus, to achieve the overall cost, energy use and GHGE savings, efforts should be directed toward improving the parameters directly impacting these three processes of the supply chain.

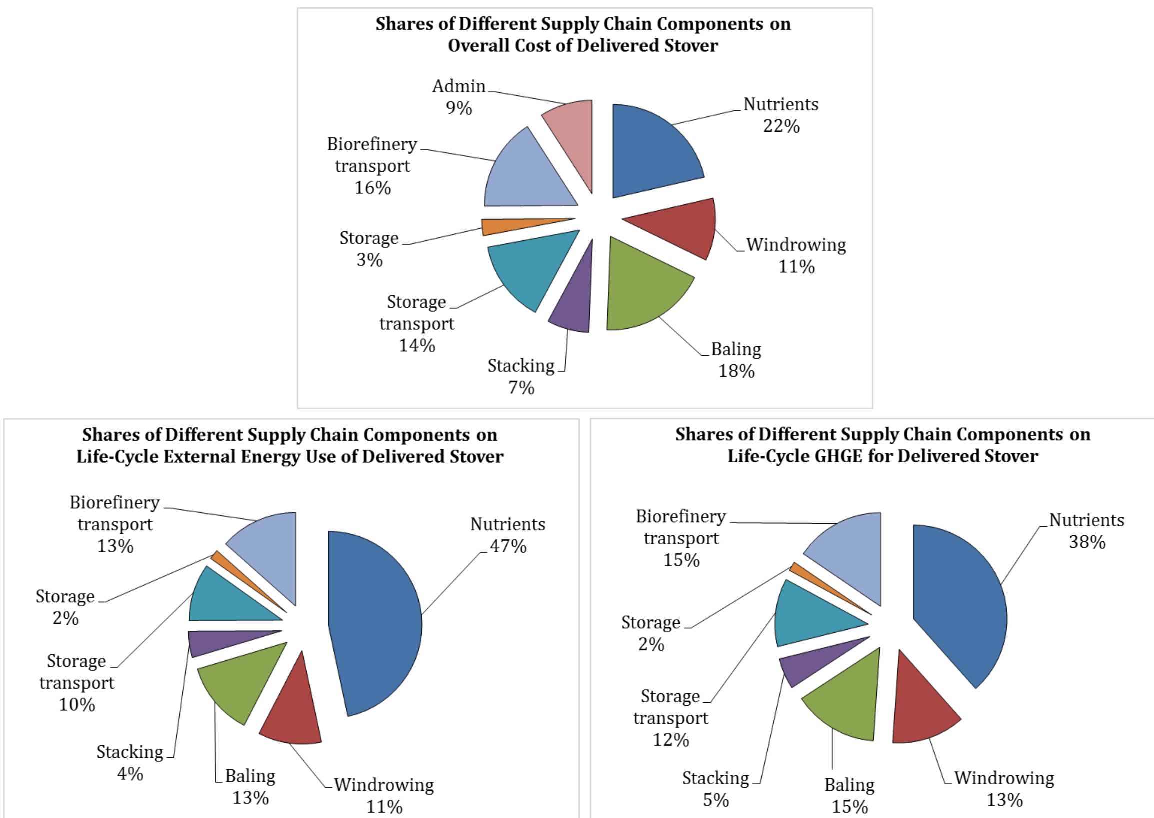

Figure 3.6: Relative shares of different components on the average overall cost, life-cycle energy use and GHGE of corn stover biomass feedstock supply chain of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery

3.6 Conclusions

Life-cycle energy use and greenhouse gas emissions (GHGE) for corn stover biomass feedstock supply chain for a Midwest-based 114 MLPY (30 MGPY) biorefinery plant are stochastically evaluated. Different components of the selected supply chain includes harvesting (windrowing and baling), in-field bales collection and stacking at the field-edge, handling and transportation of bales from the field-edge to the distributed central storage facilities and, then, to the biorefinery plant, storage, and finally the audit of nutrients removed during stover collection from the field. Average energy use, energy use ratio (EUR) and GHGE for feedstock supply chain to deliver corn stover biomass to the gate of a Midwest-based 114 MLPY (30 MGPY) biorefinery plant are estimated to be 1502 MJ std. Mg^{-1} (1.3 million BTU std. ton^{-1}), 21.0%, and 95.2 kg-CO_2e std. Mg^{-1} (190.4 lb-CO_2e std. ton^{-1}), respectively, out of which nutrients removed during stover harvest shares around 38-47%, followed by harvesting (~24-28%) and transportation (~23-27%). Average EUR for nutrients removed during stover harvest is 9.8% and is the highest among different supply chain components. For harvesting and transportation activities, EUR are around 5%, with that for baling being higher than that for windrowing, and for biorefinery transport being higher than that for storage transport. Average GHGE for the corn stover feedstock supply chain is around 15% of the emissions for gasoline including different life-cycle stages from crude oil extraction to combustion.

This study provides the estimates on life-cycle energy use and GHGE for the supply chain in current context; however, these can be reduced by exploring the ways to reduce the quantity of nutrients, mainly nitrogen, removed from the field during stover collection, optimizing the performances of different farm machineries to minimize their fuel consumptions and to maximize their productivities, and designing equipment that combine different processes of the supply chain into a single unit (ex: single-pass harvesting which integrates grain harvest, windrowing and baling processes in one piece of equipment). Additional research should be directed toward enhancing the bulk density of the feedstock which would help reduce the overall energy use and GHGE for the supply chain. Lastly, this study is based on corn stover feedstock; however, for the overall success of biobased industries, it is imperative to evaluate the environmental performances of other lignocellulosic feedstocks, especially energy crops and forest residues, and to explore the ways to create a mix of different feedstocks for biobased industries.

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3.8 Supporting Materials

3.8.1 Annual life-cycle energy use and greenhouse gas emissions (GHGE) for corn stover biomass feedstock supply chain of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery

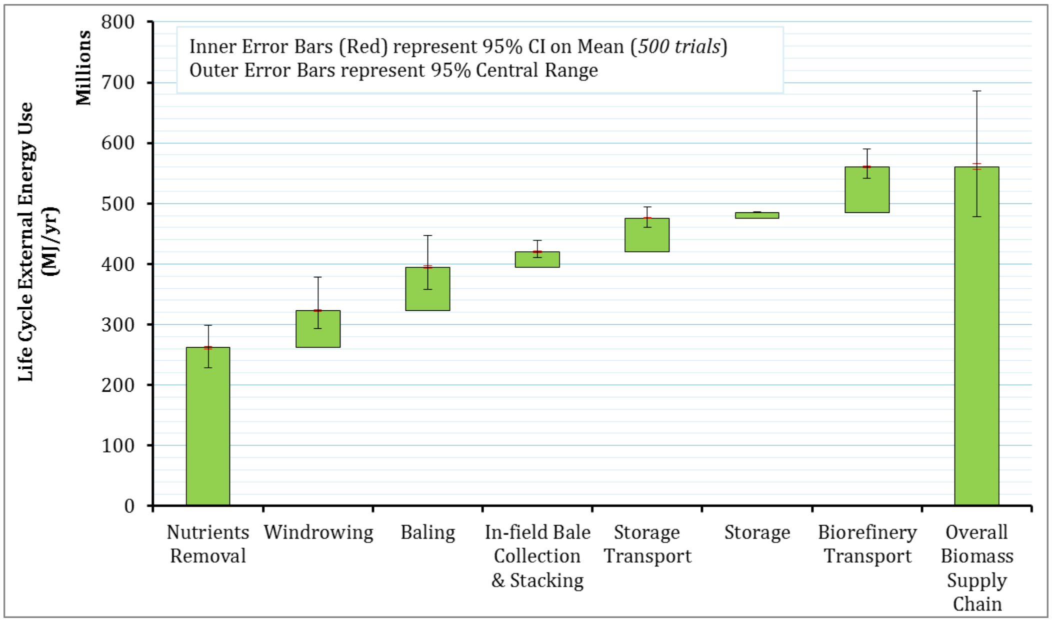

Figure S3.1: Annual life-cycle energy use for corn stover biomass feedstock supply chain of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery

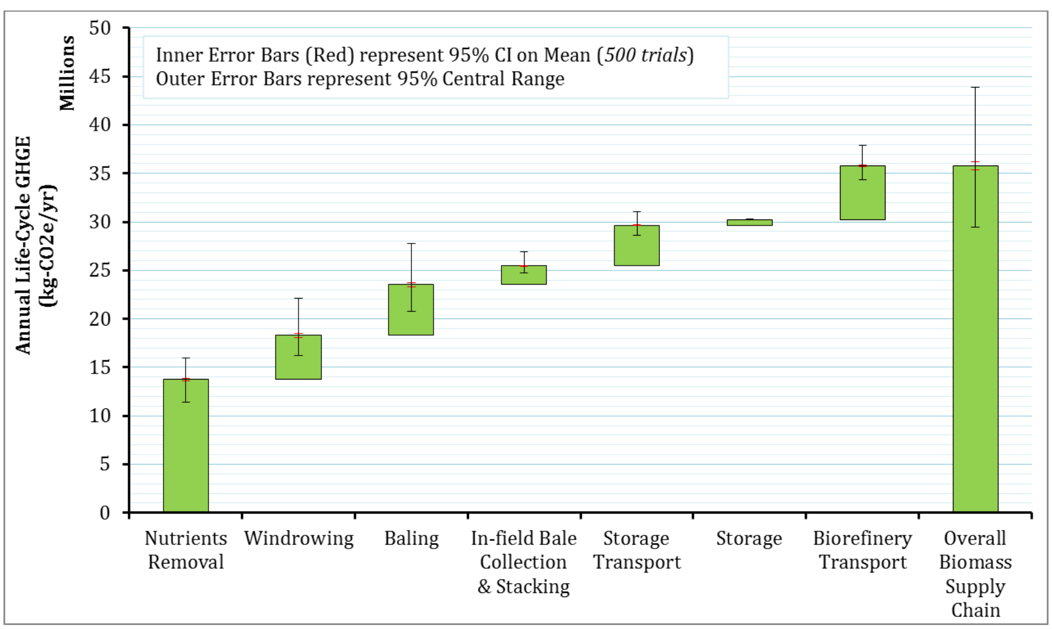

Figure S3.2: Annual life-cycle GHGE for corn stover biomass feedstock supply chain of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery

3.8.2 Life-cycle energy use and GHGE for delivering stover to a 114 MLPY (30 MGPY) biorefinery plant to produce 1 liter of cellulosic ethanol

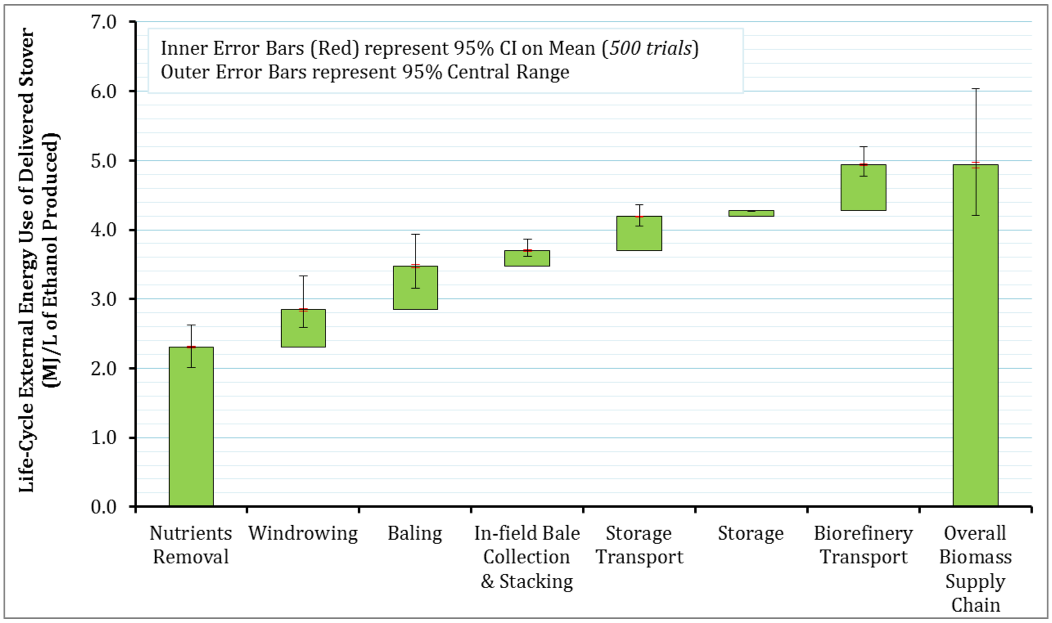

Figure S3.3: Life-cycle energy use for delivering stover to a 114 MLPY (30 MGPY) biorefinery plant to produce 1 L of cellulosic ethanol

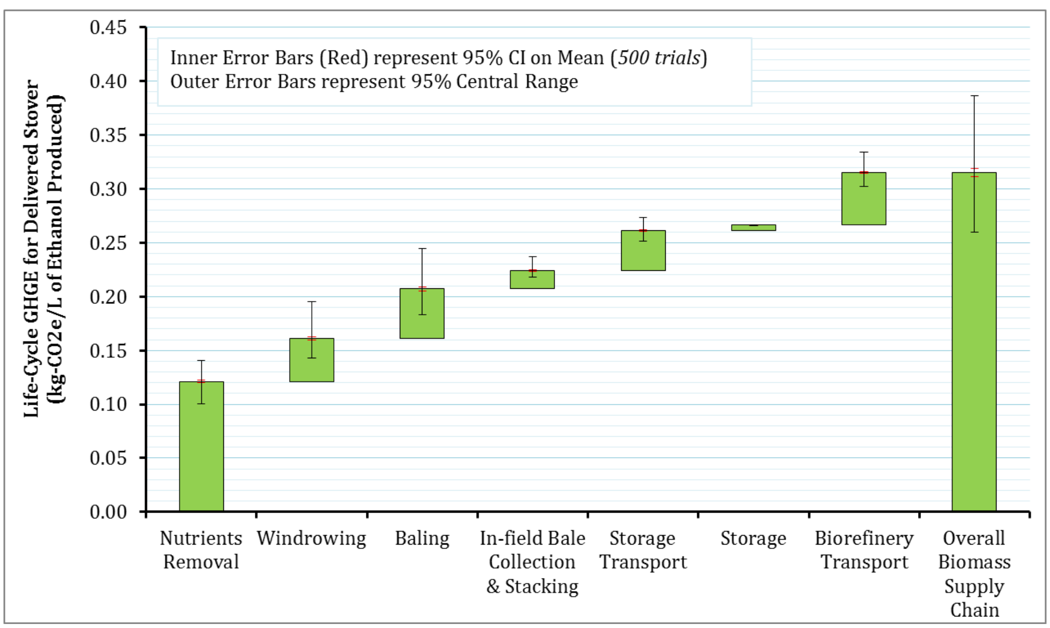

Figure S3.4: Life-cycle GHGE for delivering stover to a 114 MLPY (30 MGPY) biorefinery plant to produce 1 L of cellulosic ethanol

3.8.3 Life-cycle energy use and GHGE for different components of corn stover feedstock supply chain

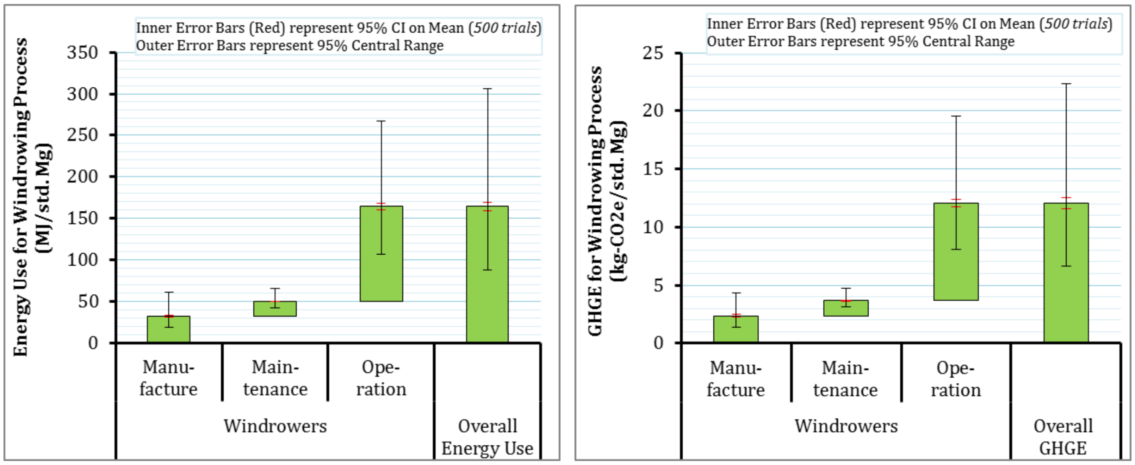

Figure S3.5: Life-cycle energy use and GHGE for the windrowing process of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) biorefinery plant

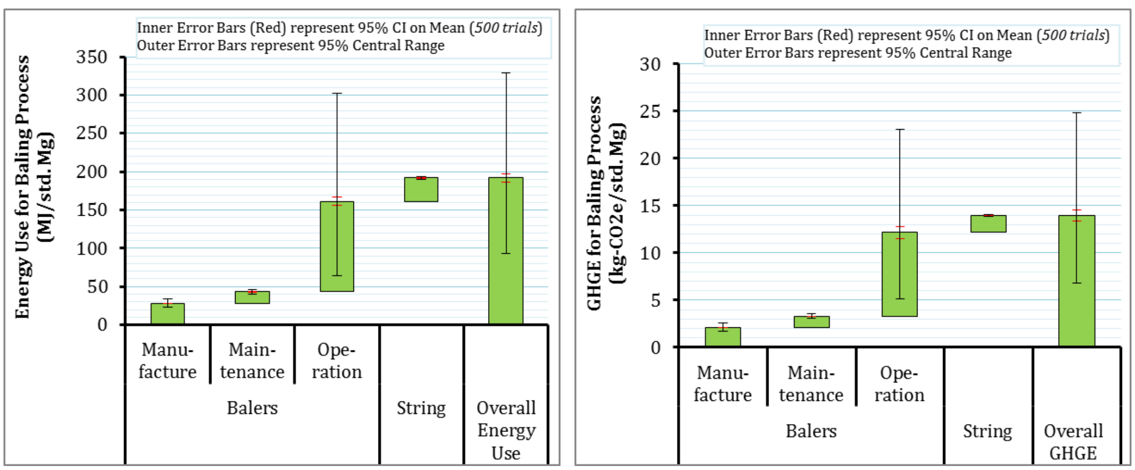

Figure S3.6: Life-cycle energy use and GHGE for the baling process of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) biorefinery plant

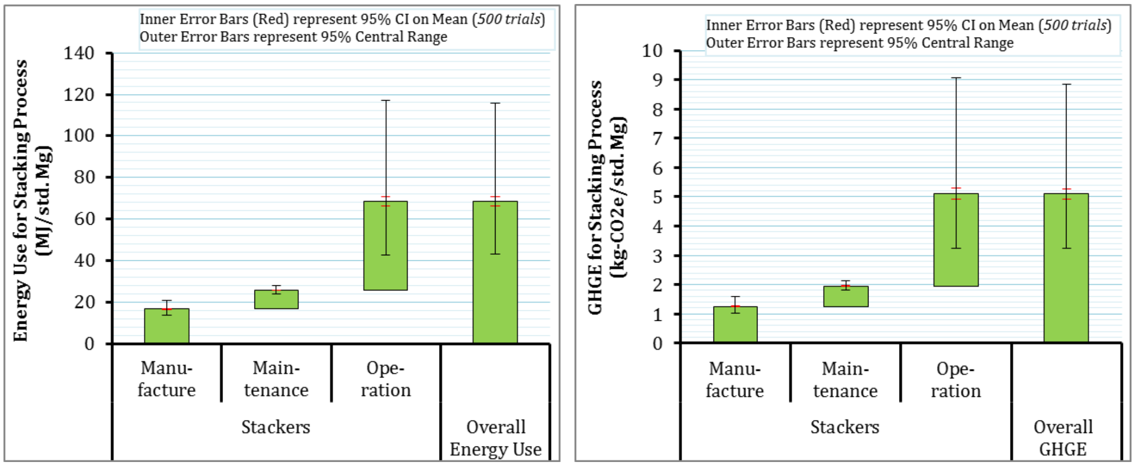

Figure S3.7: Life-cycle energy use and GHGE for the stacking process of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) biorefinery plant

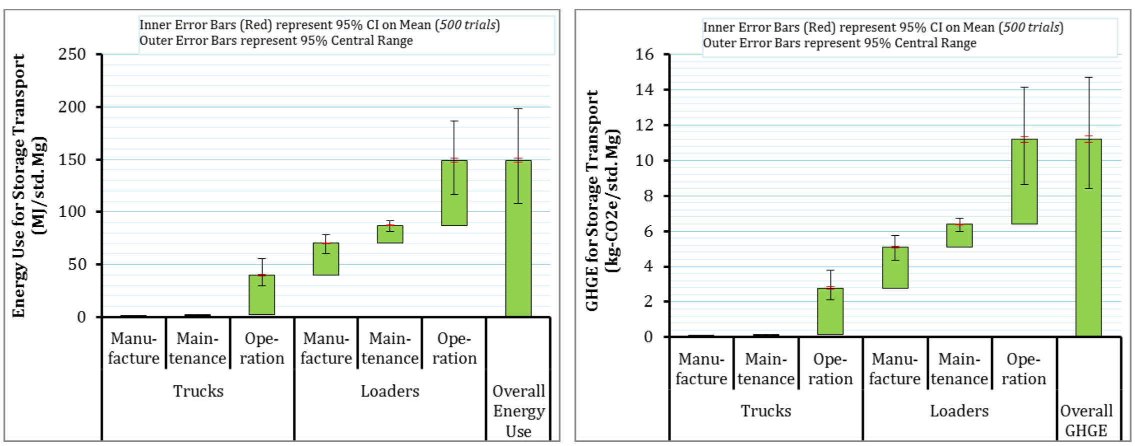

Figure S3.8: Life-cycle energy use and GHGE for the storage transport process of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) biorefinery plant

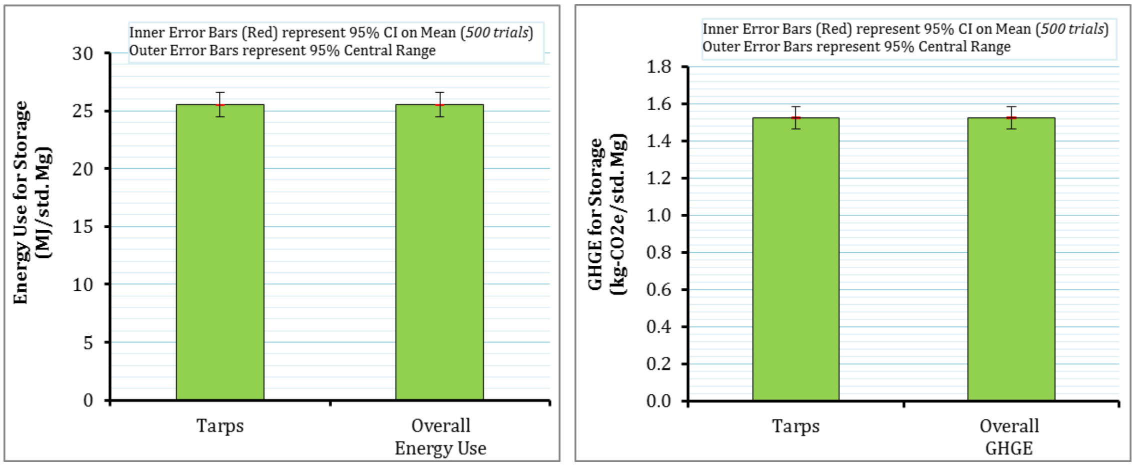

Figure S3.9: Life-cycle energy use and GHGE for the storage process of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) biorefinery plant

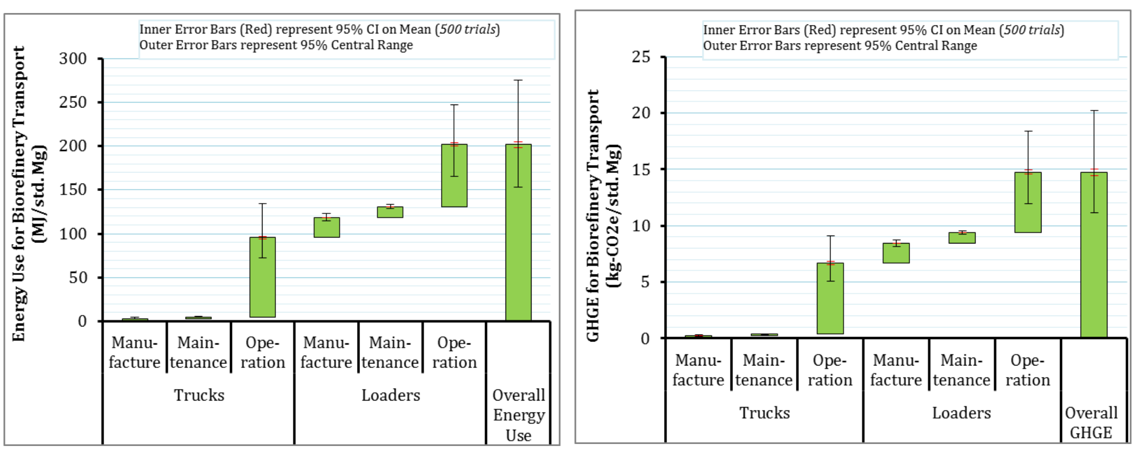

Figure S3.10: Life-cycle energy use and GHGE for the biorefinery transport process of corn stover feedstock supply chain of a 114 MLPY (30 MGPY) biorefinery plant

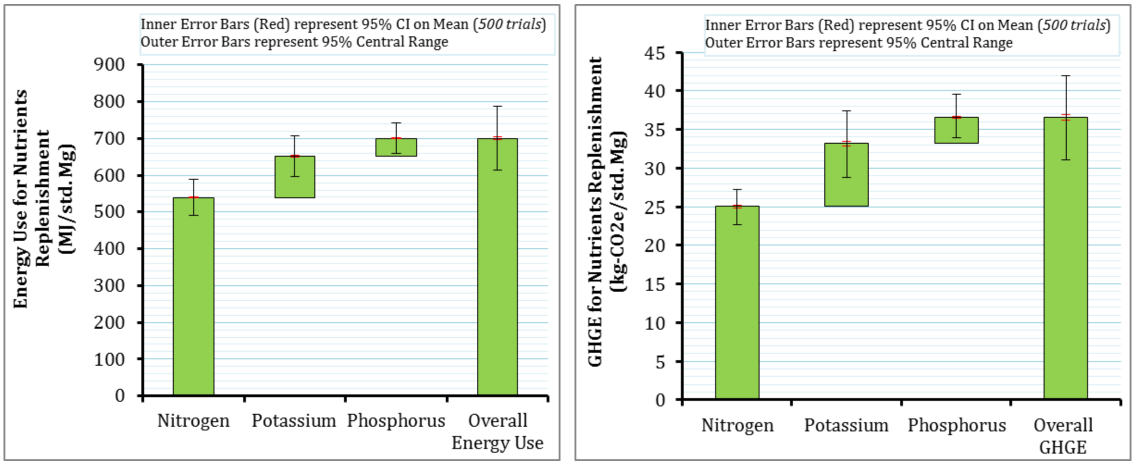

Figure S3.11: Life-cycle energy use and GHGE associated with nutrients removed during stover harvest for a 114 MLPY (30 MGPY) biorefinery plant

3.8.4 Histograms and cumulative distribution function (CDF) graphs of the main outcomes of this work, as discussed in the main body of the paper

Table S3.1: Histograms and CDF graphs of life-cycle energy use (MJ/std. Mg) for corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

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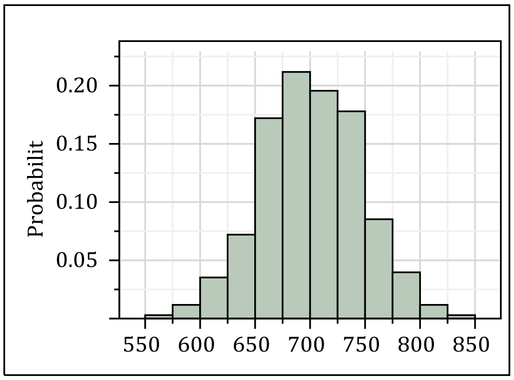
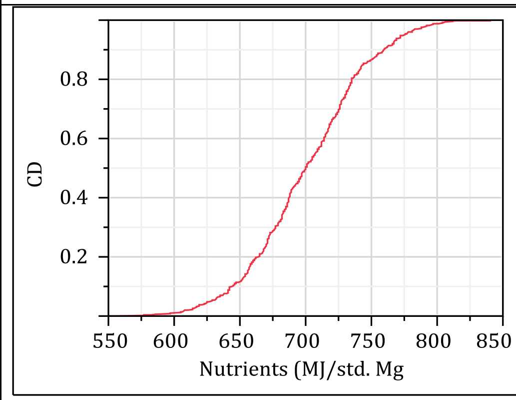
<tr><td>Nutrients replenishment</td><td>
</td><td>
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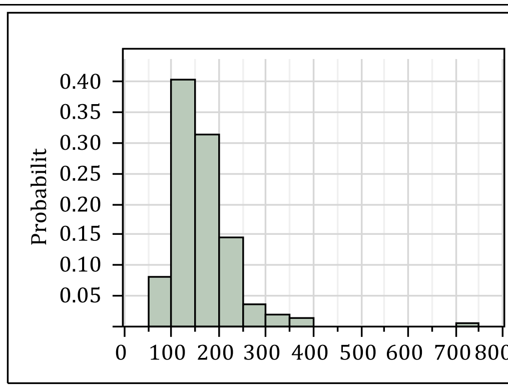
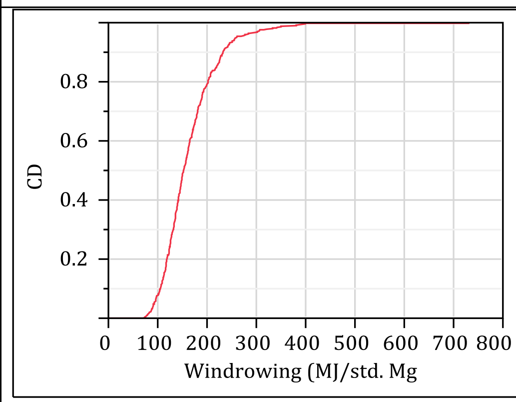
<tr><td>Windrowing</td><td>
</td><td>
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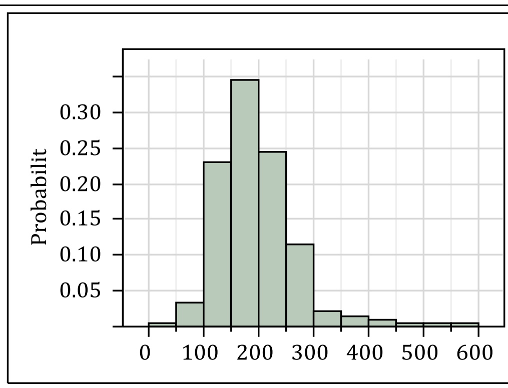
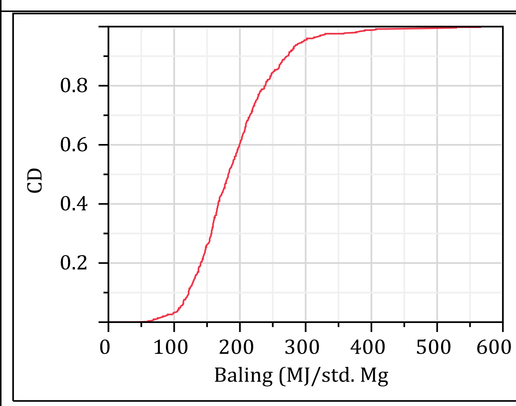
<tr><td>Baling</td><td>
</td><td>
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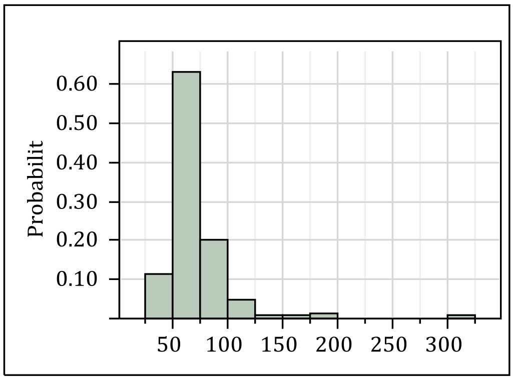
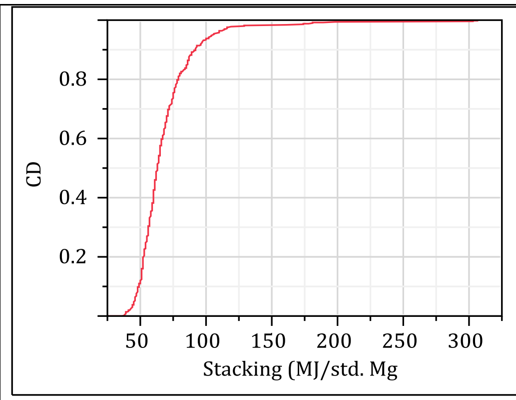
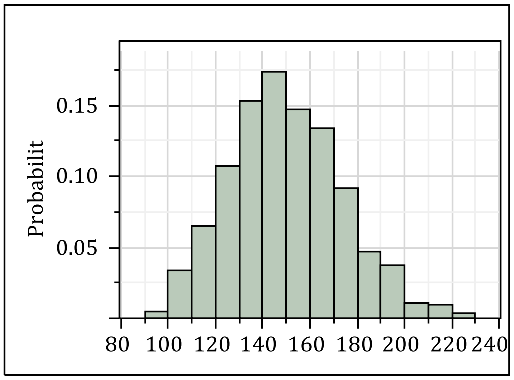
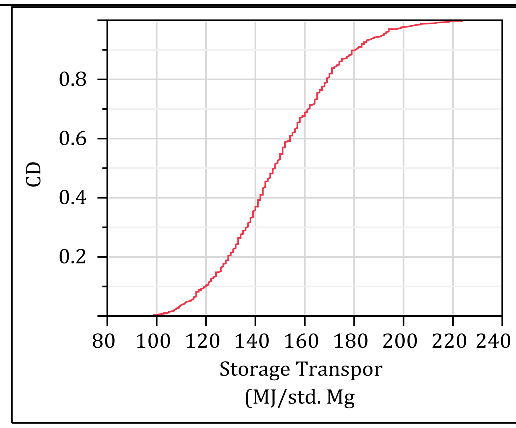
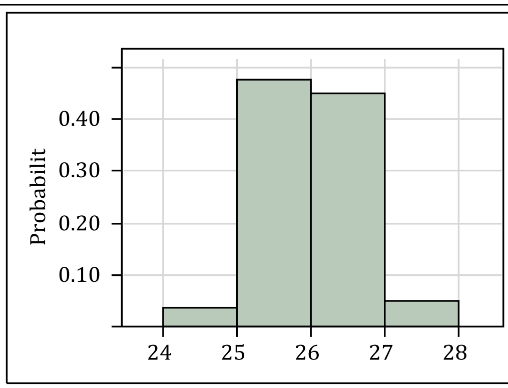
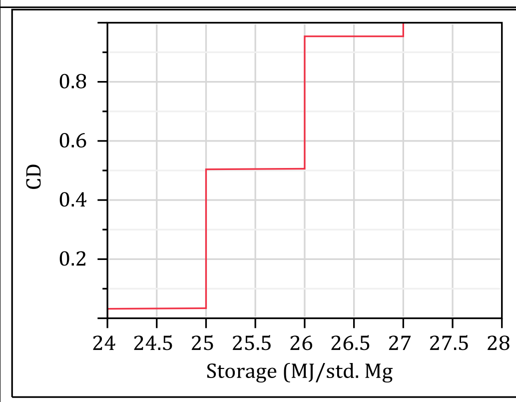
Stacking		
Storage transport		
Storage		

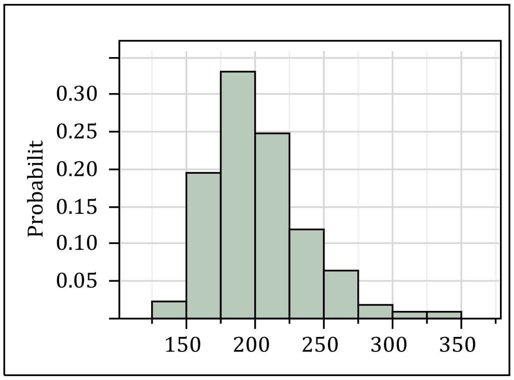
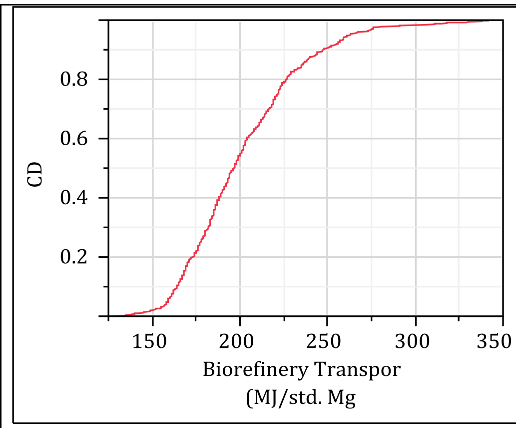
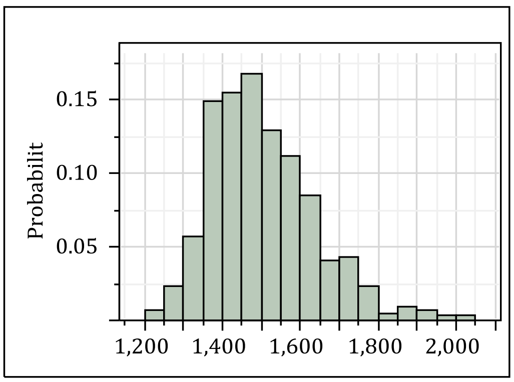
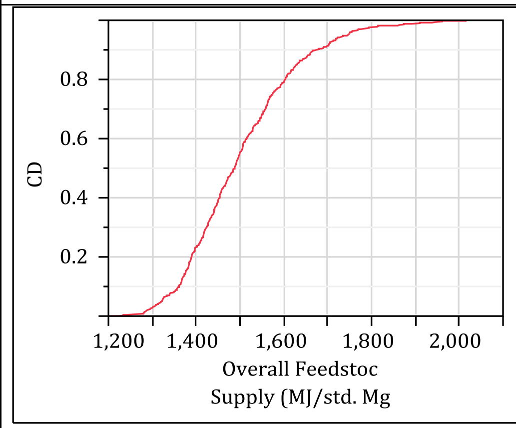
Biorefinery transport		
Entire supply chain		

Table S3.2: Histograms and CDF graphs of life-cycle GHGE (kg-CO_2e/std. Mg) for corn stover feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

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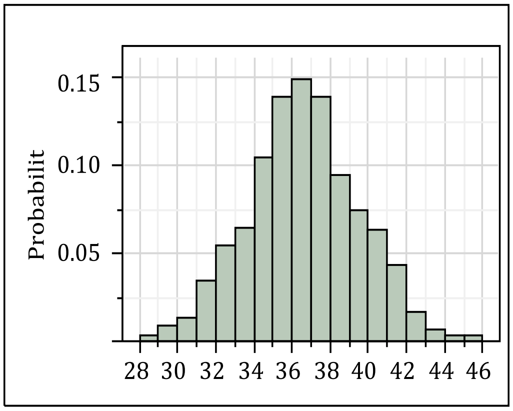
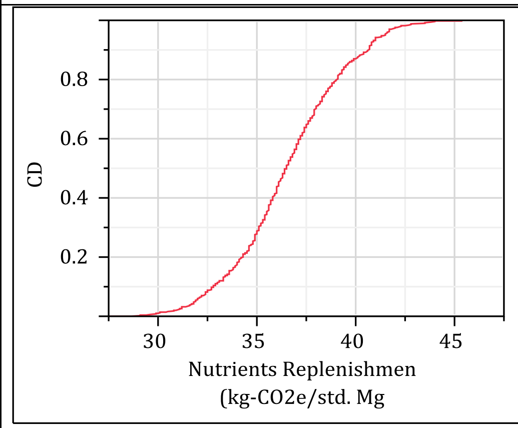
<tr><td>Nutrients replenishment</td><td>
</td><td>
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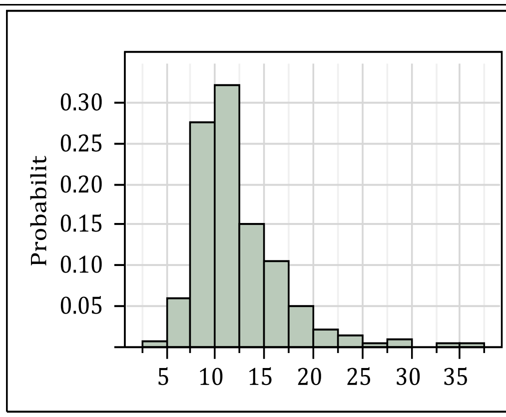
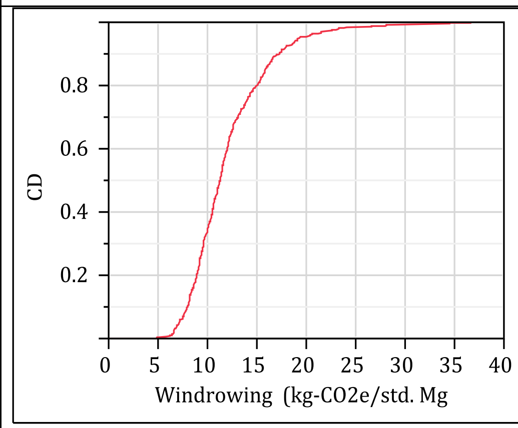
<tr><td>Windrowing</td><td>
</td><td>
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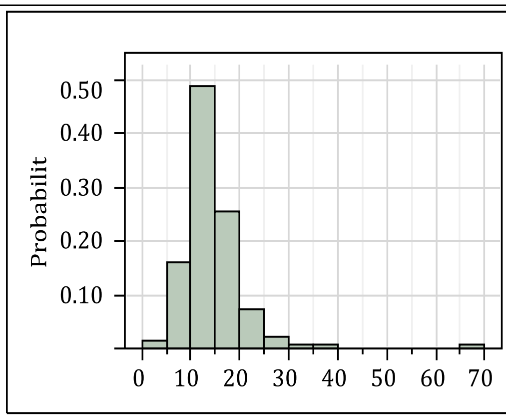
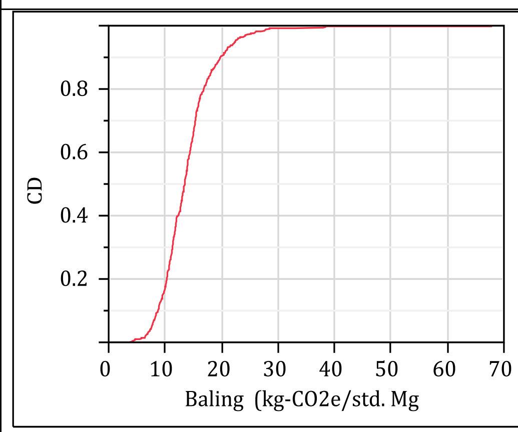
<tr><td>Baling</td><td>
</td><td>
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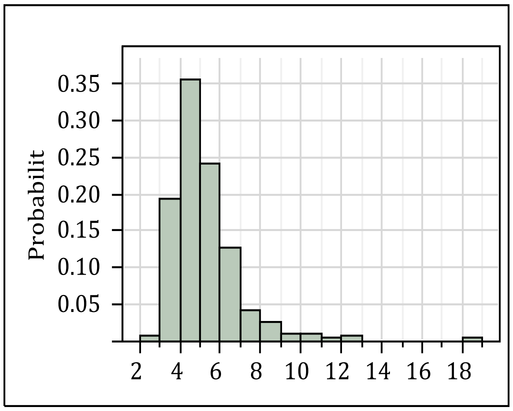
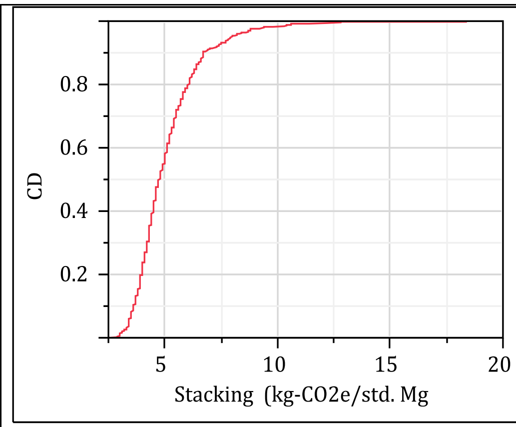
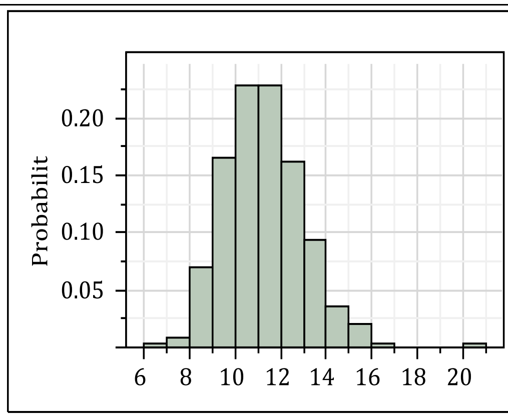
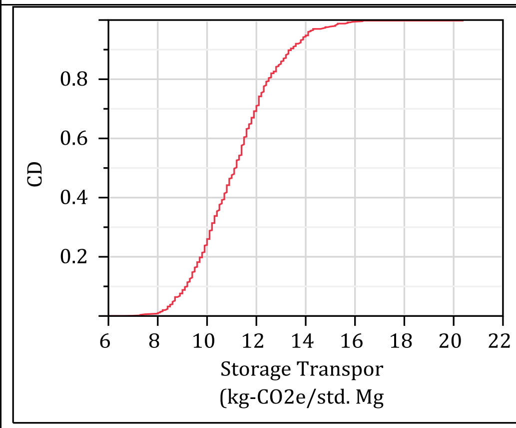
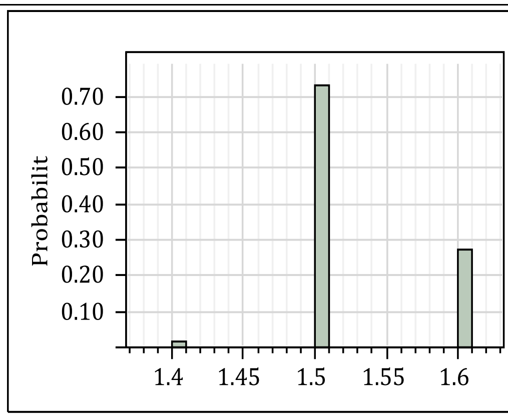
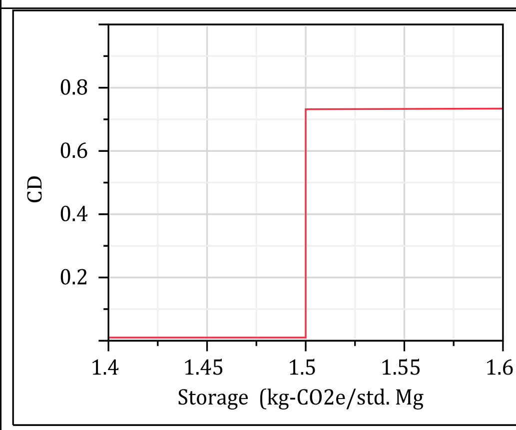
Stacking		
Storage transport		
Storage		

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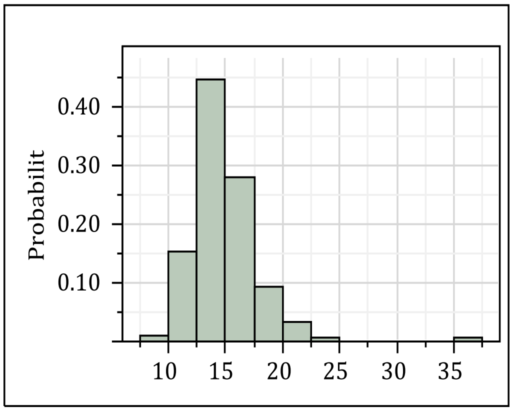
<td>
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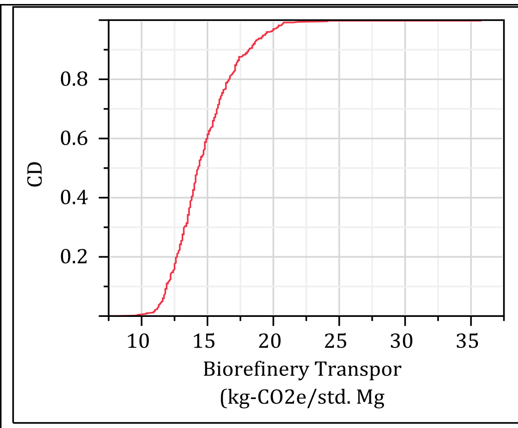
<td>
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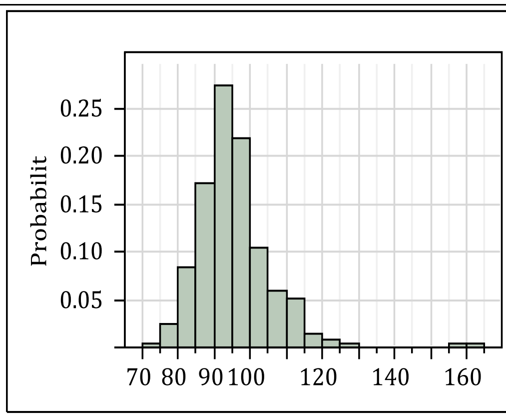
<td>
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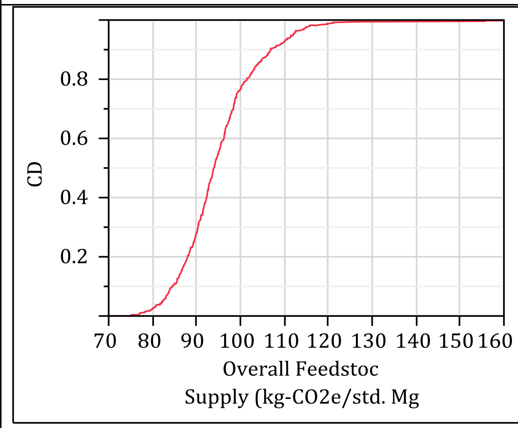
<td>
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Table S3.3: Histograms and CDF graphs of energy use ratio (EUR, %) for corn stover biomass feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery plant

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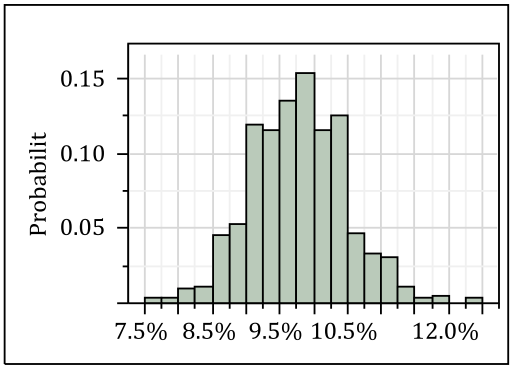
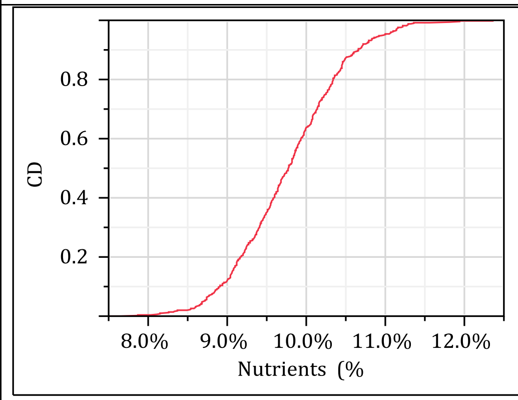
<tr><td>Nutrients replenishment</td><td>
</td><td>
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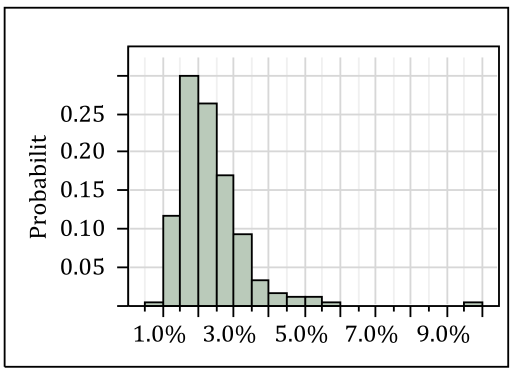
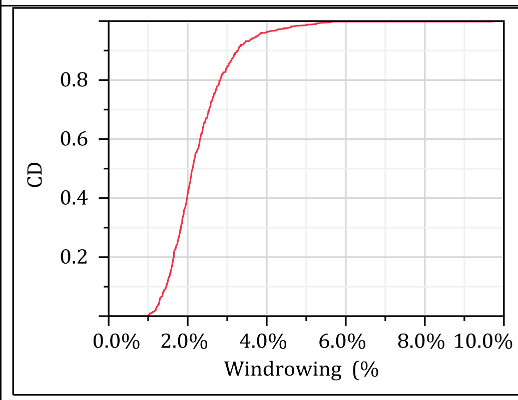
<tr><td>Windrowing</td><td>
</td><td>
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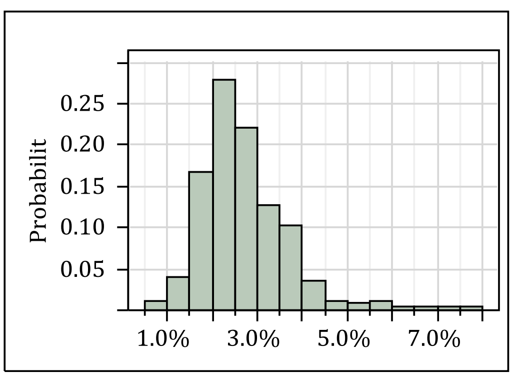
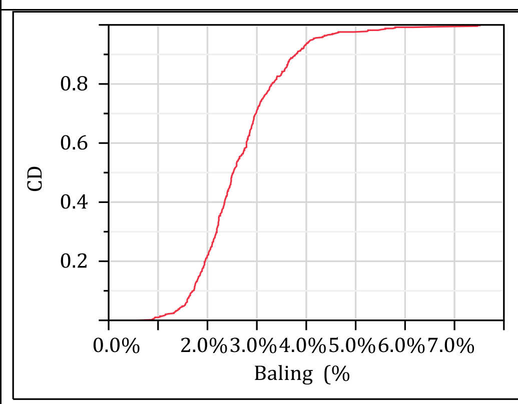
<tr><td>Baling</td><td>
</td><td>
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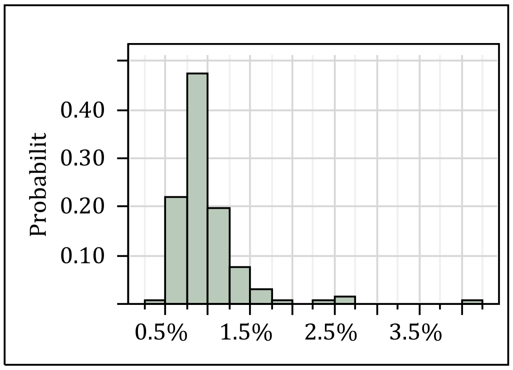
<td>
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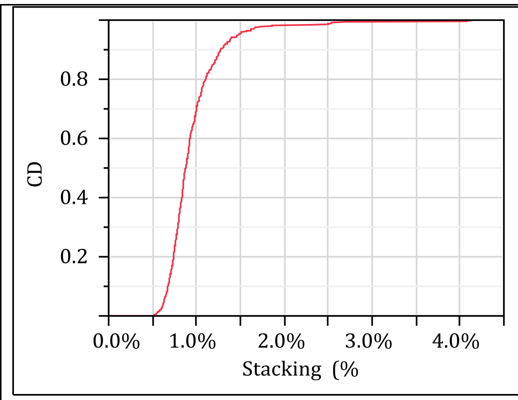
<td>
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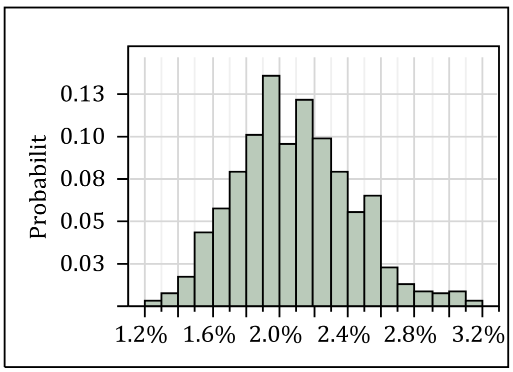
<td>
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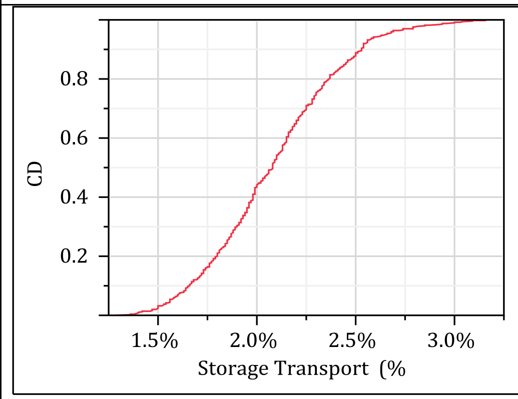
<td>
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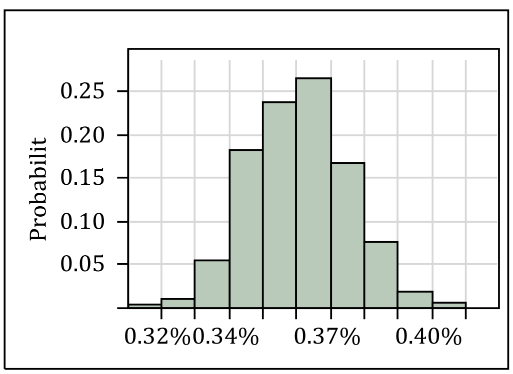
<td>
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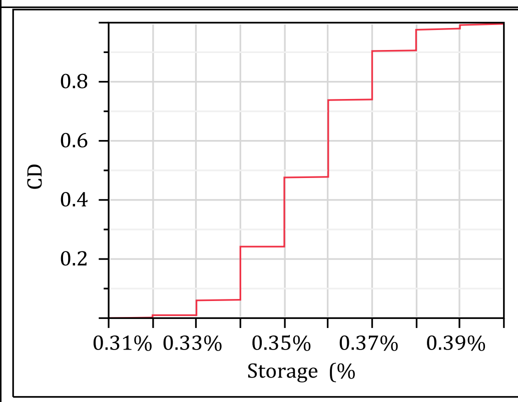
<td>
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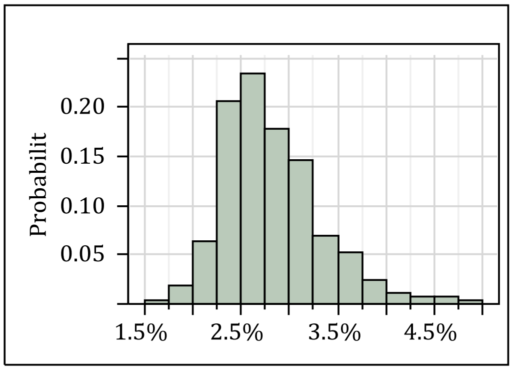
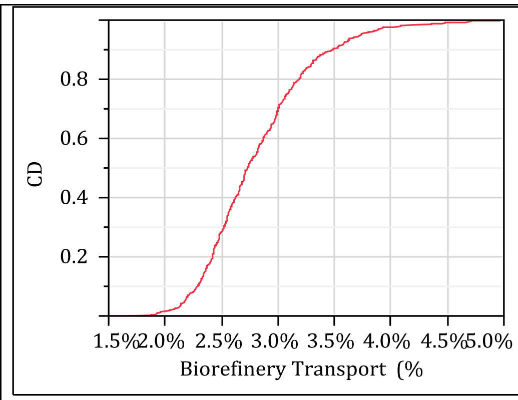
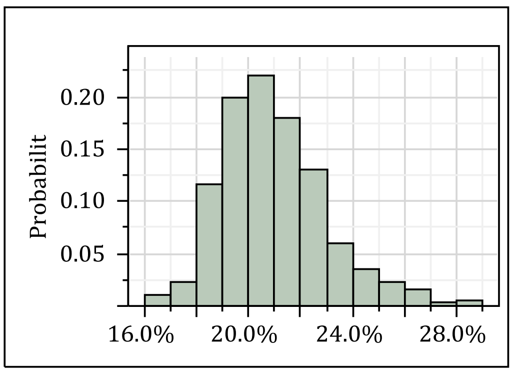
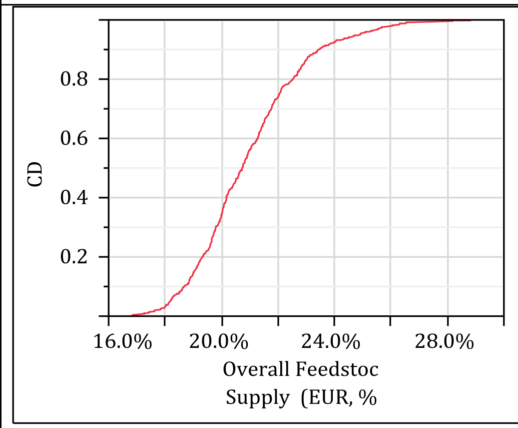
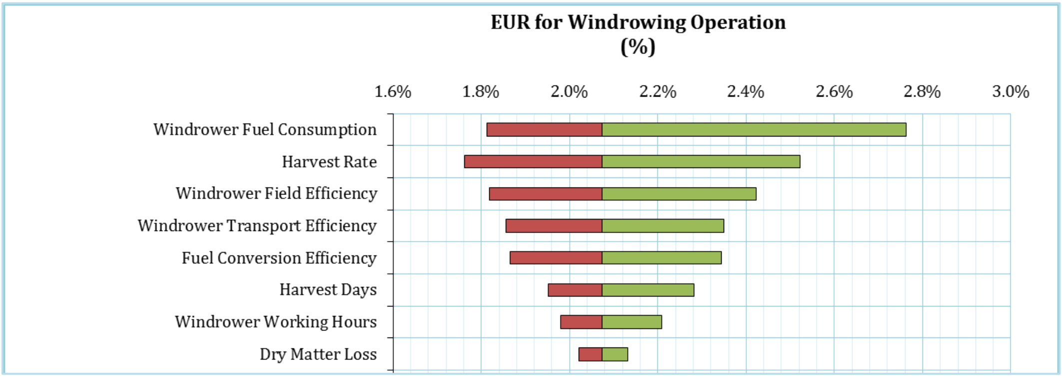
Biorefinery transport		
Entire supply chain		

3.8.5 Sensitivity analysis results for life-cycle energy use (in terms of EUR) and GHGE of different corn stover supply chain components



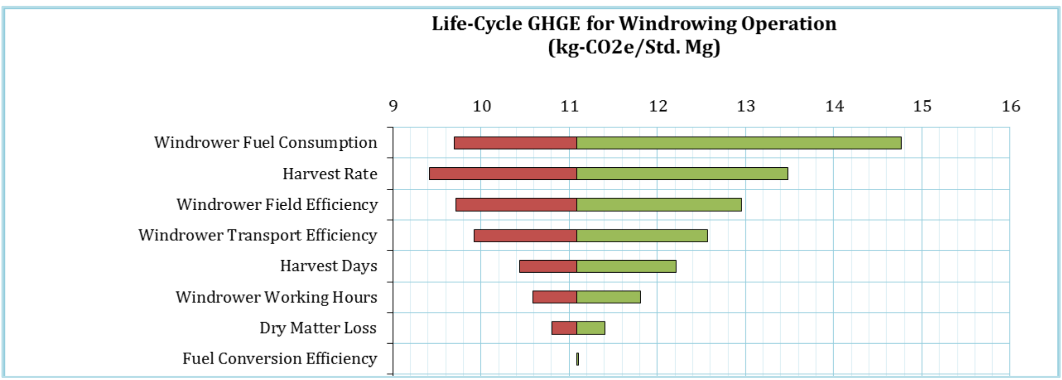


Figure S3.12: Sensitivity of EUR and GHGE for windrowing process of feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

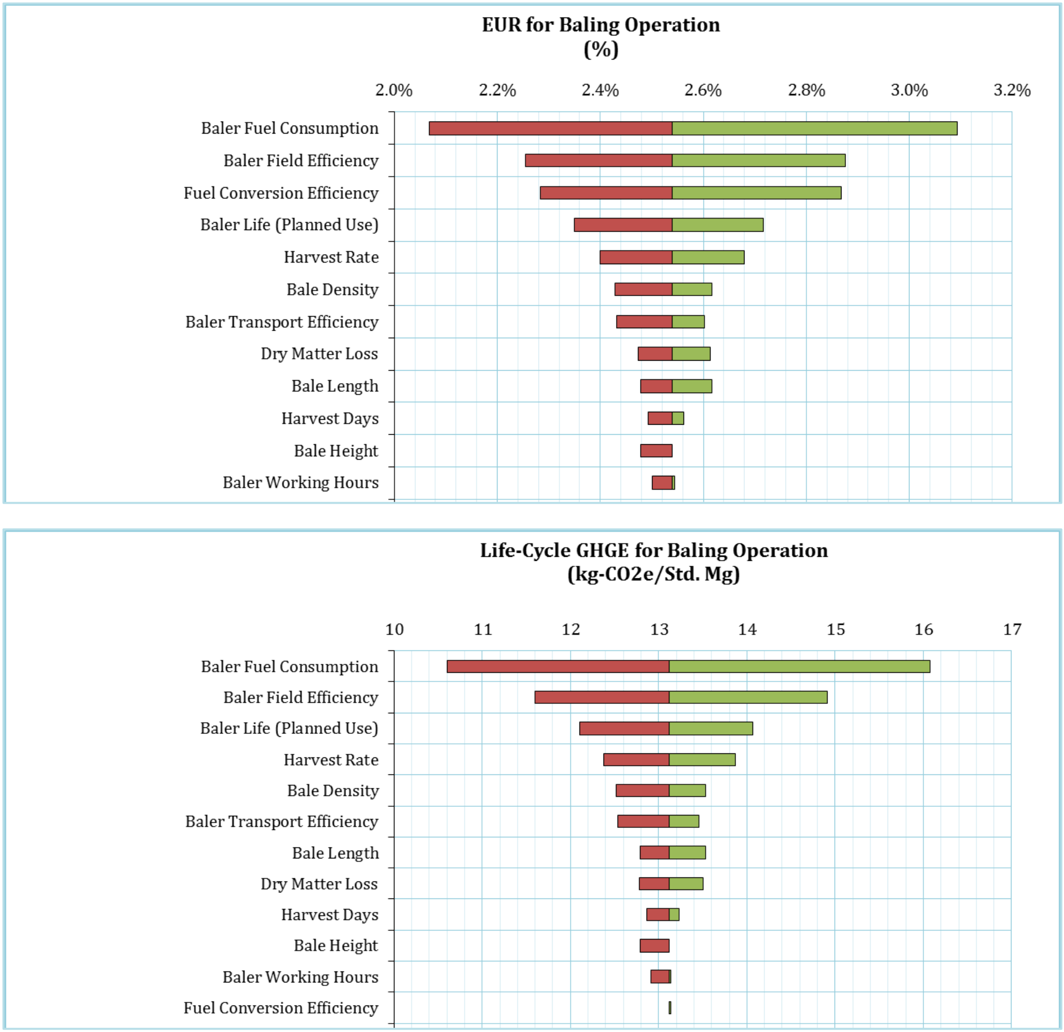
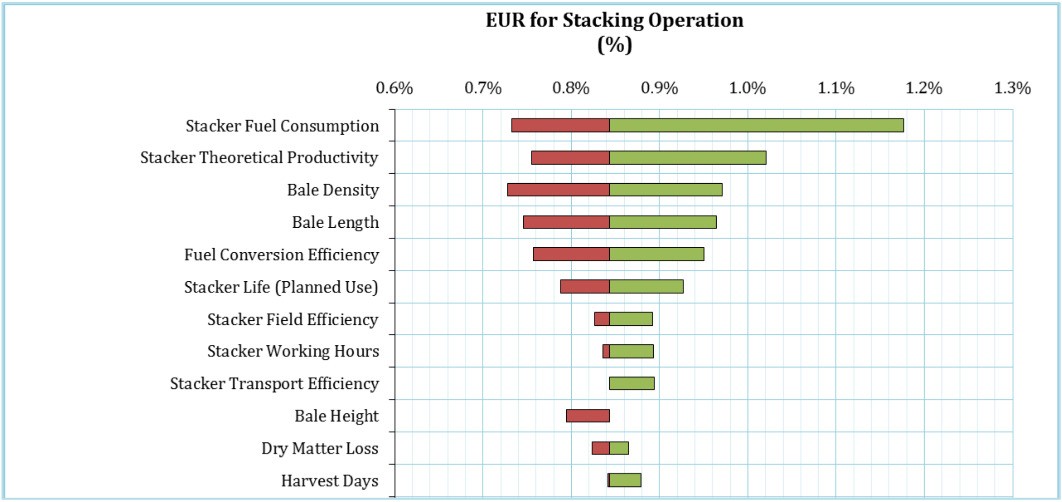


Figure S3.13: Sensitivity of EUR and GHGE for baling process of feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters



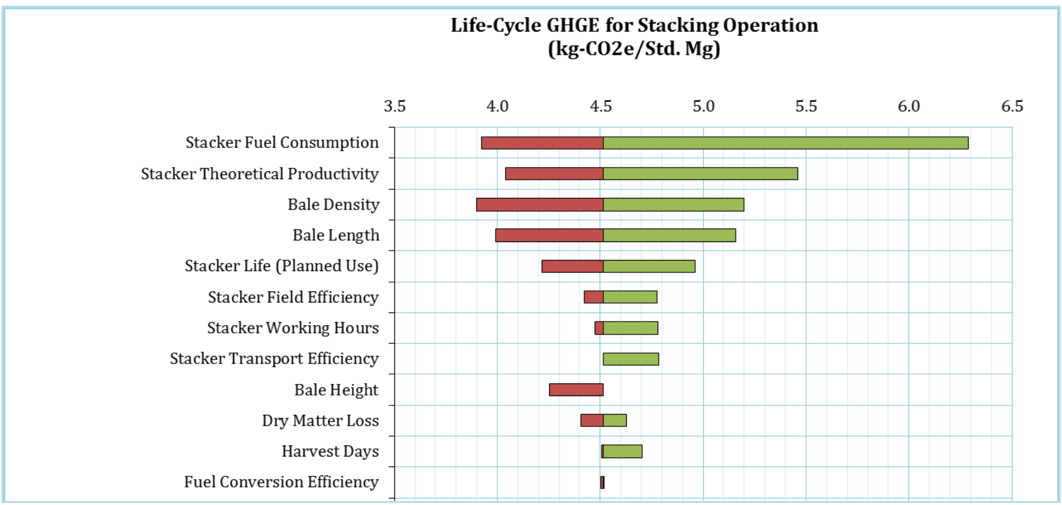
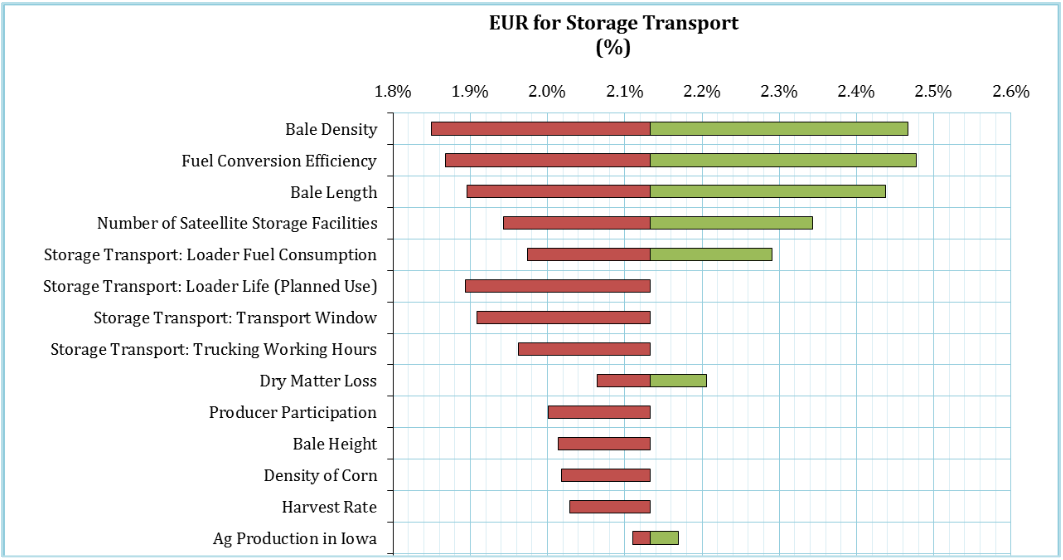


Figure S3.14: Sensitivity of EUR and GHGE for stacking process of feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters



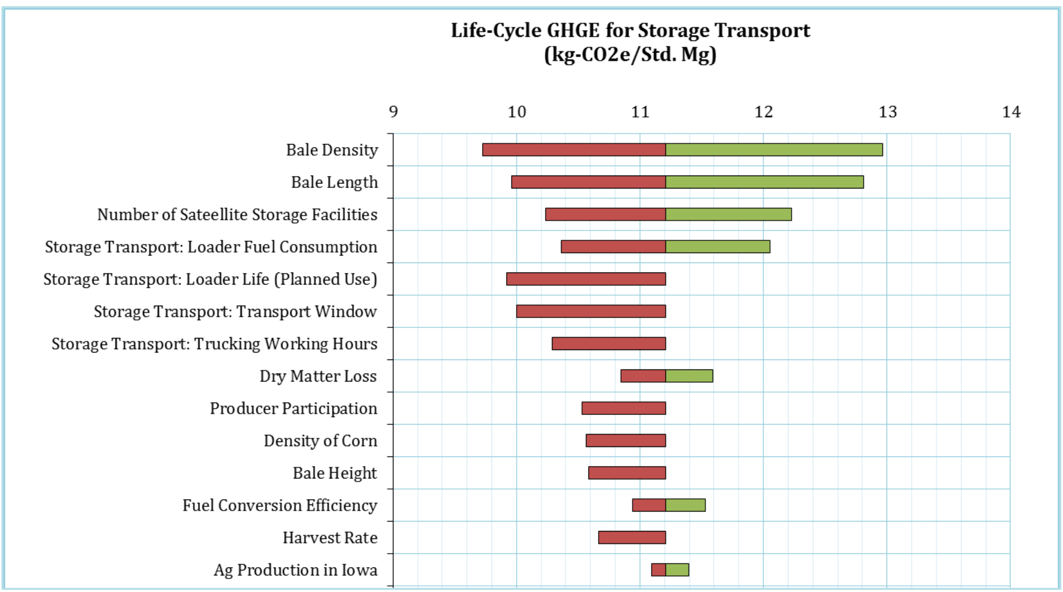


Figure S3.15: Sensitivity of EUR and GHGE for storage transportation process of feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

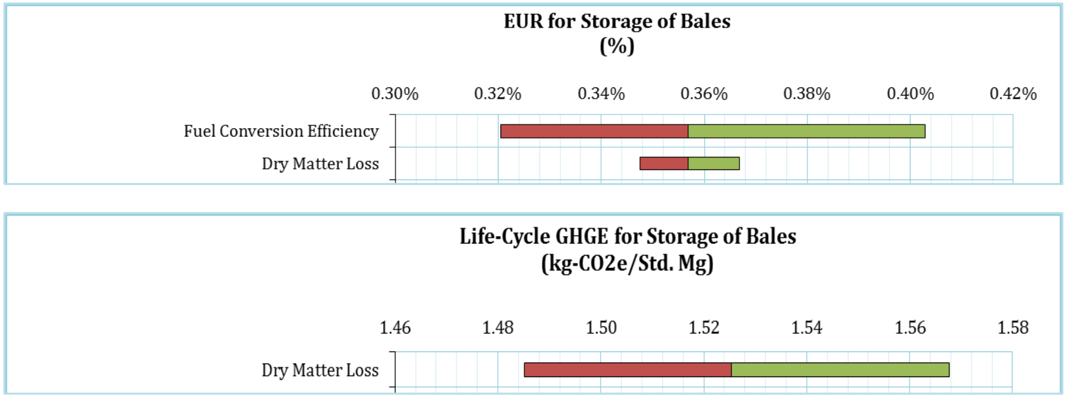


Figure S3.16: Sensitivity of EUR and GHGE for storage process of feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

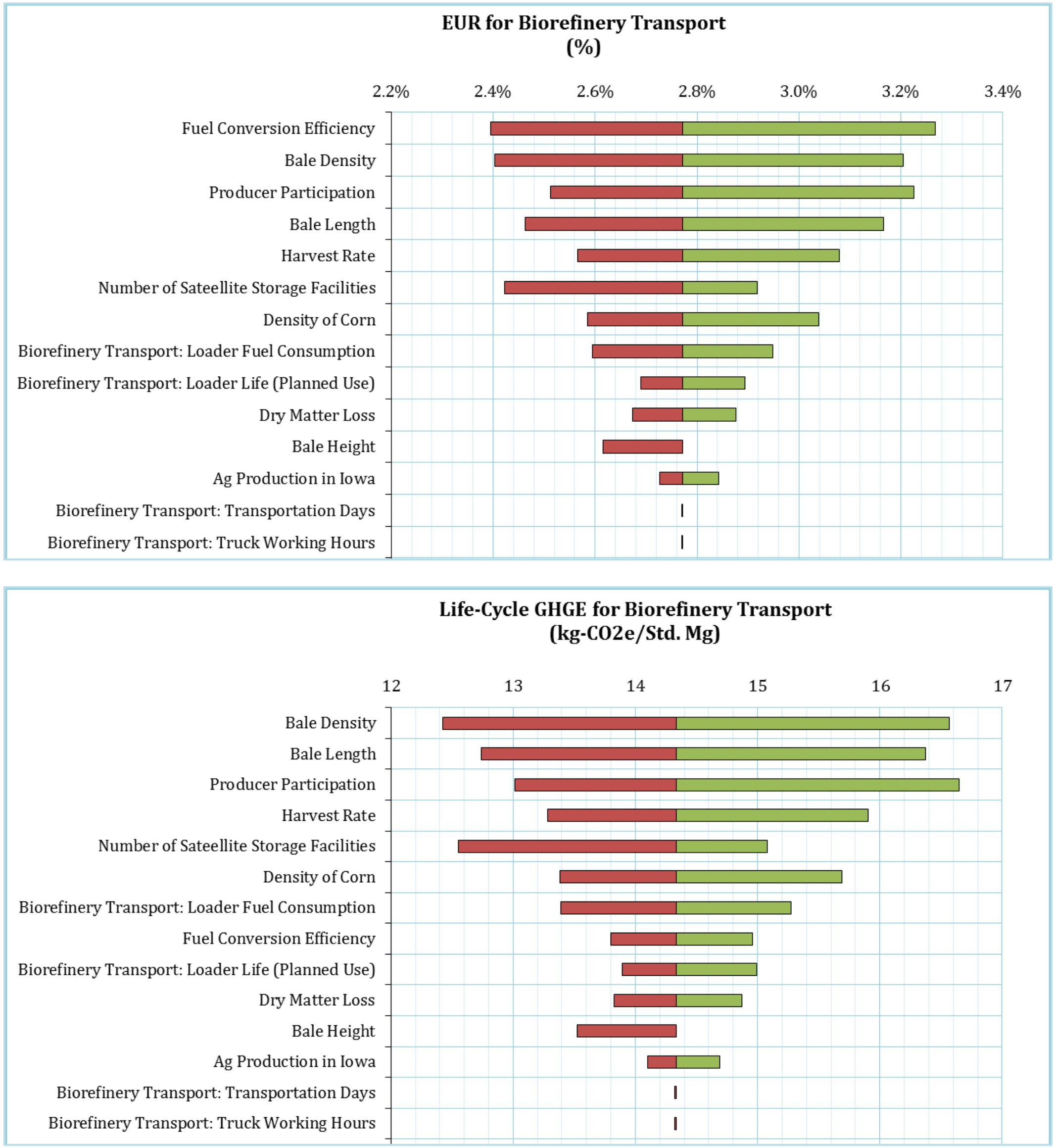
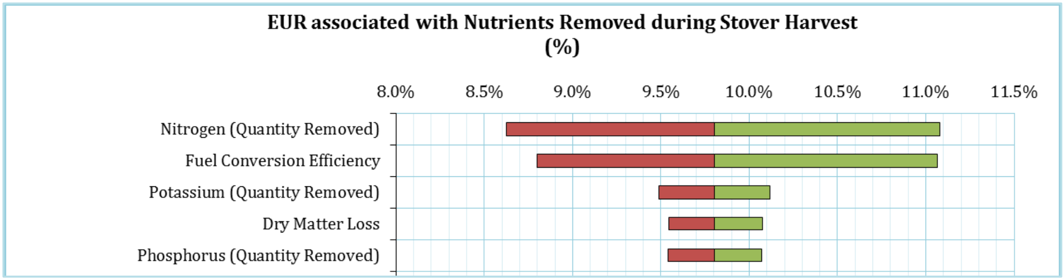


Figure S3.17: Sensitivity of EUR and GHGE for biorefinery transportation process of feedstock supply chain of a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters



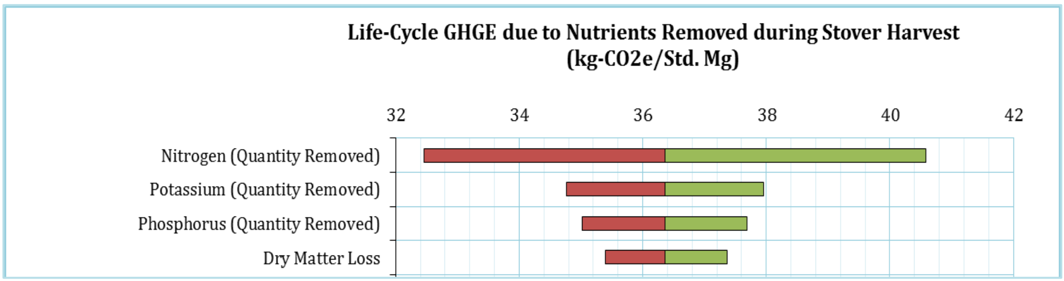


Figure S3.18: Sensitivity of EUR and GHGE for nutrients removed during stover harvest to supply feedstock to a 114 MLPY (30 MGPY) cellulosic biorefinery on different system parameters

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

4.1 Conclusions

Corn stover biomass will be the primary feedstock choice of the first-generation cellulosic biorefineries in the Midwestern United States. Thus, for uninterrupted operation of these plants, year-round supply of corn stover needs to be secured, which will require a robust, efficient, cost-effective and environmentally-balanced feedstock supply chain. This dissertation stochastically analyzes the current techno-economics, and life-cycle energy use and greenhouse gas emissions (GHGE) of corn stover biomass feedstock supply chain of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery plant using production-scale field data collected in Iowa. Different components of this supply chain include corn stover harvesting (windrowing and baling), in-field bales collection and stacking at the field-edge, handling and transportation of bales from the field-edge to the distributed central facilities for storage and, then, to the biorefinery plant, and finally the audit of nutrients removed during stover collection from the field. Major deliverables from this study include the estimates on resources (feedstock, machineries, labor and fuel) requirements, and the cost, life-cycle energy use and GHGE for this feedstock supply chain. Energy use results are also presented in terms of energy use ratio (EUR), which this dissertation defines as the ratio of the external energy used by the feedstock supply chain to deliver stover to the biorefinery gate to produce cellulosic ethanol and the overall energy content of the produced ethanol. Furthermore, this study carries out sensitivity analysis to gauge the impacts of different supply chain parameters on different output metrics. In addition to these, this dissertation lays out some of the potential strategies to optimize different supply chain parameters to receive overall savings in cost, energy and GHGE.

A Midwest-based 114 MLPY cellulosic biorefinery plant, on an average, requires around 374 thousand std. Mg (413 thousand std. ton) corn stover feedstock each year. Accounting for supply chain dry matter loss, supplying this quantity requires around 404 thousand std. Mg (445 thousand std. ton) corn stover biomass harvested each year, which is equivalent to around 0.95 million large rectangular bales. To supply this quantity of bales to the biorefinery gate, feedstock supply chain, on an average, requires around 149 windrowers, 134 balers, 56 stackers, 85 trucks and 56 loaders for storage transportation, and 25 trucks and 12 loaders for biorefinery transportation. Execution of different activities of the feedstock supply chain of a 114 MLPY cellulosic biorefinery, on an average, requires around 250 thousand hours equivalent of labor and 4.3 million L (1.2 million gal) of diesel fuel each year. Around 90% of the average overall labor and fuel requirements of the supply chain are due to the harvesting and transportation operations. In addition to these findings, average cost, energy use, EUR and GHGE for delivering corn stover feedstock to the gate of a Midwest-based 114 MLPY cellulosic biorefinery are estimated to be 121.9 \$-std. Mg^{-1} (110.6 \$-std. ton^{-1}), 1502

MJ std. Mg^{-1} (1.3 million BTU std. ton^{-1}), 21%, and 95.2 kg-CO_2e std. Mg^{-1} (190.4 lb-CO_2e std. ton^{-1}), respectively. Furthermore, among different feedstock supply chain systems parameters, bale density and length, harvest rate, baler field efficiency and fuel consumption, dry matter loss, quantity of nitrogen removed from the field during stover collection, and harvest window are identified to be the top five parameters with regards to influencing the overall cost, energy use and GHGE for biorefinery gate delivered feedstock.

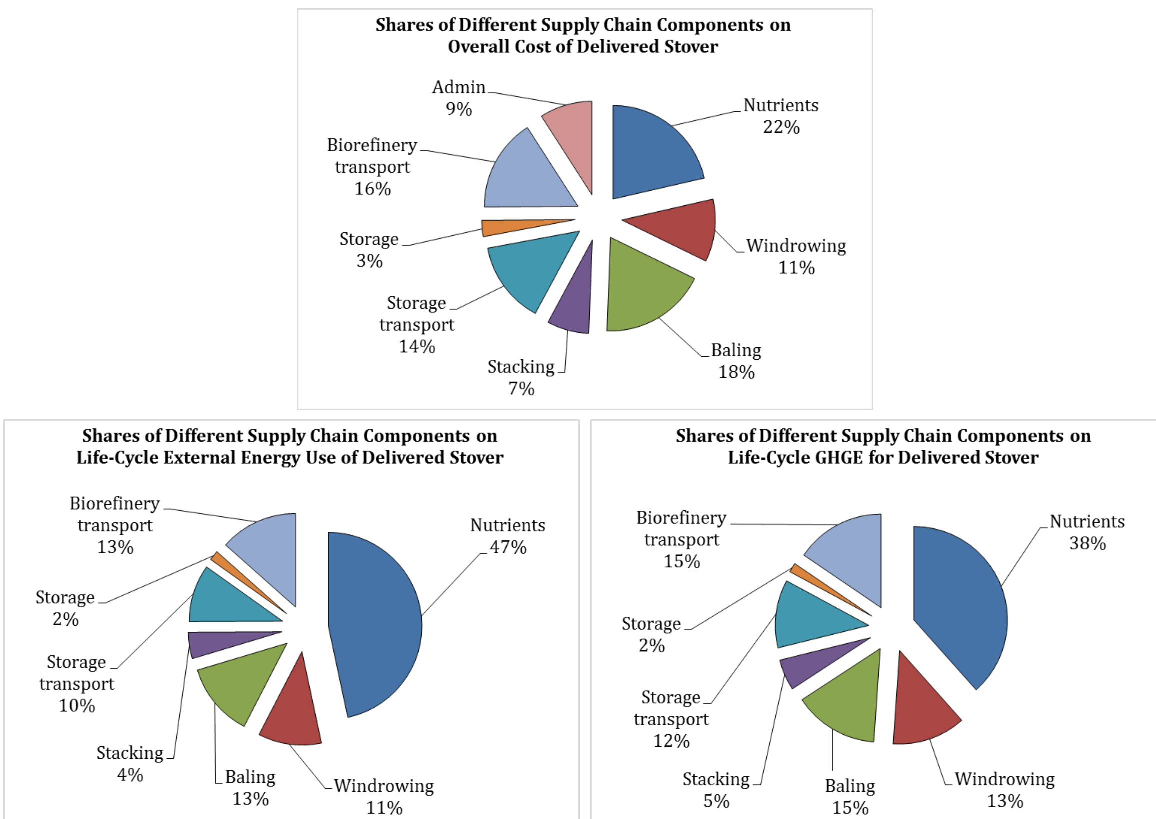


Figure 4.1: Relative shares of different components on the average overall cost, life-cycle energy use and GHGE of corn stover biomass feedstock supply chain of a Midwest-based 114 MLPY (30 MGPY) cellulosic biorefinery (Note: *This figure has been adopted from the Chapter 3 of this dissertation*)

Figure 4.1 summarizes the contributions of different components of the supply chain on its overall cost (obtained using results from Chapter 2 of this dissertation) and life-cycle energy use and GHGE (obtained using results from Chapter 3 of this dissertation). In cost perspective, the two activities related to corn stover harvesting (i.e., windrowing and baling) and the two activities associated with transportation (i.e., storage and biorefinery transportations) share around 30% of the overall supply chain cost followed by 22% for nutrients; and, in life-cycle energy use and GHGE perspective, nutrients alone contribute to 38-47% of the life-cycle energy use and GHGE for the overall supply chain, followed by around 23-28% for each harvesting and transportation activities. Out of the total life-cycle energy use and GHGE associated with nutrients, 68-77% is contributed by nitrogen alone. In addition to these, comparing with gasoline on an energy content per unit volume basic, in the present context, biorefinery gate delivered feedstock cost will be around 69% of the ethanol price to be cost competitive with gasoline. Additionally, average GHGE for the corn stover feedstock supply chain as estimated in this dissertation is around 38% of the overall GHGE target set by EISA (2007) for cellulosic biofuels production, distribution and utilization. EISA (2007) has set the target to reduce the GHGE from cellulosic biofuels at least by 60% than that from gasoline. Thus, the overall cost and GHGE for feedstock supply chain is significant, and, if not given serious consideration, supplying feedstock for biorefinery purpose can be a limiting factor for the successful commercial deployment and sustainability of the complete cellulosic biofuels production and utilization cycle.

4.2 Recommendations for future work

This dissertation analyzes the techno-economics, and life-cycle energy use and GHGE for the supply chain of a Midwest-based 114 MLPY cellulosic biorefinery in current context, and the methodology as well as findings of this study can be utilized as a reference for furthering the knowledgebase of this area in twofold. First, by improving different supply chain systems parameters, and, next, by optimizing the overall feedstock supply chain for cost, energy use and GHGE reductions. Successful implementation of these two strategies will require research efforts directed toward production-scale field tests recognizing the scale of feedstock supply chain operations required by the future cellulosic biorefineries. Currently, most of the studies are primarily based on small-scale operations which fail to capture the scale of operation anticipated for supplying feedstock for cellulosic biorefineries. Data obtained from the production-scale field tests will enhance the confidence on the estimates under uncertainties, as well as help in improving the current standards relating to different feedstock supply chain operations. Current standards are based on the small-scale operations, primarily focused on providing solutions to feedstock collection for cattle feeds and bedding needs, and do not necessarily and sufficiently capture the scale of different supply chain operations for biobased industries anticipating commercial deployment in the near future.

Building upon the findings of this study some future research efforts on improving the supply chain systems parameters can be directed toward reducing the overall supply area for feedstock, decreasing the overall quantities of bale to be supplied to the biorefineries for meeting their demand, and reducing the quantities of farm machineries required for different supply chain activities. Overall feedstock collection area for biorefineries can be reduced by increasing producer's participation and sustainable harvest rate, and by reducing the dry matter loss (DML), especially during storage of feedstock. Overall quantities of bale to be supplied to biorefineries for meeting their demand can be decreased by enhancing bale density, increasing its length and height, and identifying or developing suitable equipment for safe handling of extended bales, as well as by reducing DML. And, the quantities of farm machineries required for different supply chain activities can be reduced by reducing the overall quantities of bales, increasing the working durations, optimizing the performances of different farm machineries to minimize their fuel consumptions and to maximize their productivities and efficiencies, and designing equipment that combine different processes of the supply chain into a single unit (ex: single-pass harvesting which integrates grain harvest, windrowing and baling processes in one piece of equipment). Some of the ways to achieve the aforementioned improvements are thoroughly discussed in Chapters 2 and 3 of this dissertation. In addition to these, ways to reduce the quantity of nutrients, mainly nitrogen, removed from the field with stover collection need to be scientifically explored.

Analysis presented in this dissertation can be used as a reference for further optimization of the overall corn stover biomass supply chain and to extend the analyses to the other feedstock types, including other agricultural residues, forest residues, and annual and perennial energy crops, as well as to create a mix of different feedstock for biobased industries. This study has been carried out in Iowa, a principal corn growing Midwestern state; however, the analysis presented in this dissertation can be extended to the other geographical regions across the United States. In the near term, feedstock supply chain considered in this study will be the most likely choice of the biorefineries; but, in the long run, increase in biofuels production capacities of the technologically-advanced and matured biorefineries will result in increased feedstock demand, and, thus, the supply chain discussed in this study will start to be cost prohibitive, primarily, due to increase in the feedstock transportation costs. In such scenarios, feedstock preprocessing step (densification or upgrading) will most likely be incorporated early in the supply chain. Supply chain discussed in this study will also be the part of the future feedstock supply solutions, but dominated by the ones incorporating feedstock preprocessing step. Thus, the future research need to be focused toward assessing the production-scale data-driven techno-economics and life-cycle energy use and GHGE of the supply chain systems with additional feedstock preprocessing steps. Inclusion of feedstock preprocessing step early in the supply chain will also open up opportunities for choosing alternative transportation modes (rail, barge, pipeline) for preprocessed feedstock. Thus, research efforts should also be directed toward determining the break-even points for the implementation of different transportation modes, as well as alternative supply chain systems with regards to optimizing cost, energy use and GHGE of the overall feedstock supply complex.