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Corn stover availability for biomass conversion: situation analysis

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Abstract As biorefining conversion technologies become commercial, feedstock availability, supply system logistics, and biomass material attributes are emerging as major barriers to the availability of corn stover for biorefining. While systems do exist to supply corn stover as feedstock to biorefining facilities, stover material attributes affecting physical deconstruction, such as densification and post-harvest material stability, challenge the cost-effectiveness of present-day feedstock logistics systems. In addition, the material characteristics of corn stover create barriers with any supply system design in terms of equipment capacity/efficiency, dry matter loss, and capital use efficiency. However, analysis of a conventional large square bale corn stover feedstock supply system concludes that (1) where other agronomic factors are not limiting, corn stover can be accessed and supplied to a biorefinery using existing bale-based technologies, (2) technologies and new supply system designs are necessary to overcome biomass bulk density and moisture material property challenges, and (3) major opportunities to improve conventional bale biomass feedstock supply systems include improvements in equipment efficiency and capacity and reducing biomass losses in harvesting, collection, and storage. Finally, the backbone of an effective stover supply system design is the optimization of intended and minimization of unintended material property changes as the corn stover passes through the individual supply system processes from the field to the biorefinery conversion processes.

Keywords Feedstock logistics · Corn stover · Harvesting · Collection · Storage · Preprocessing · Transportation

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Introduction

The United States is increasing the use of lignocellulosic biomass as part of a portfolio of solutions to address climate change issues and improve energy security, in addition to other benefits that an invigorated agricultural industry can provide. A number of studies have defined bioenergy/biofuel production targets that are in line with the aim to displace 30% of the 2004 gasoline use with biofuels (60 billion gal/year) by 2030 (Fales et al. 2007; DOE-EERE 2009). Of that 60 billion gallons, 15 billion are projected to come from grains, with the remaining 45 billion from lignocellulosic resources (73 FR 226 2008). This means that of the 700 million tons of biomass required to be delivered to biorefineries annually, 530 million tons will come from lignocellulosic resources.

Corn stover (the stalks, leaves, and cobs that remain after corn grain is harvested) is a substantial source of lignocellulosic biomass. In the United States, about 75 million dry matter (DM) tons of the corn stover residue produced annually could be used for biofuels (Perlack et al. 2005). With technology and land-use improvements, the estimated future production potential of corn stover is greater than 170 million DM tons (Perlack et al. 2005). Presently, the corn stover biofuels potential is about 6 billion gallons (85 gal/ton) and is projected to reach about 15 billion gallons in the future (90 gal/ton; DOE-EERE 2009). This ethanol production potential provides a significant amount of feedstock for meeting renewable fuel standard goals (73 FR 226 2008), thus making corn stover a resource of interest for the emerging lignocellulosic biofuels industry.

One of the principle challenges of establishing corn stover as a feedstock for a self-sustaining biofuels enterprise is organizing the logistics of the feedstock supply system in a way that maintains the economic and ecological viability of supply system infrastructures while providing the needed quantities of stover resources. There are a number of constraints to consider in developing a stover-for-fuel market in relationship to cost efficiency and agronomic and environmental sustainability. With regard to cost efficiency, feedstock logistics costs must improve to the point of consuming no more than 25% of the production cost of biofuels (Fales et al. 2007; DOE-EERE 2009). This paper analyzes a corn stover supply system to determine to what extent conventional corn stover supply system technologies can achieve this cost and identify opportunities and barriers that can be addressed to achieve this target.

This analysis discusses the final delivered feedstock cost to the conversion facility as two independent calculations: "grower payment" and "supply system logistics."

Grower payment

"Grower payment" refers to the financial compensation paid to the producer to cover the costs of producing the biomass. The estimated grower payment will, for the most part, reflect the minimum price for which a grower can sell his corn stover residue and recover the direct and indirect costs of production, which is necessary to maintain a sustainable farming enterprise. However, the actual grower payment price may vary due to residue density and availability, competition for the feedstock in other uses (such as animal bedding), and the presence of alternative or substitute biofuel feedstocks (i.e., market price).

Grower payments are difficult to assess because there are no major markets for crop residues or related biomass feedstocks, such as energy crops, from which to impute a value. In the absence of any formal market prices for corn stover residue, one way to calculate the grower payment is to estimate the nutrient and organic matter values of the removed residues and add a value for grower profit.

In some situations, it may be possible to quantify the effect that leaving or removing the residue has on subsequent field operations. If left onsite to decompose, crop residues are a source of nutrients for future crops. However, when residues are collected and removed, additional fertilizer needs to be applied to make up for the nutrient loss. Crop residue removal may also affect subsequent field operations and production. For example, if some residue is removed in the fall, spring soil may dry and/or warm more quickly, allowing for earlier spring field work, earlier planting, and earlier seed germination, resulting in higher yields. Residue removal may also make herbicides more effective or require less to be applied (i.e., less herbicide is applied to residues and more is applied to its intended target). In a negative way, residue removal may increase soil compaction with additional equipment traffic and reduced organic matter near the soil surface (Wilhelm et al. 2004). All of these factors will impact the grower payment cost, and the opportunity costs need to be carefully considered when determining how much stover can be removed (stover removal limit) without negatively impacting future crop production.

Supply system logistics

"Supply system logistics" refers to the processes, capital, and operating costs associated with getting the stover resource from its production location to the in-feed system of the conversion process at the biorefinery. The feedstock supply system processes can be generally grouped into five unit operations (Hess et al. 2003; Fig. 1):

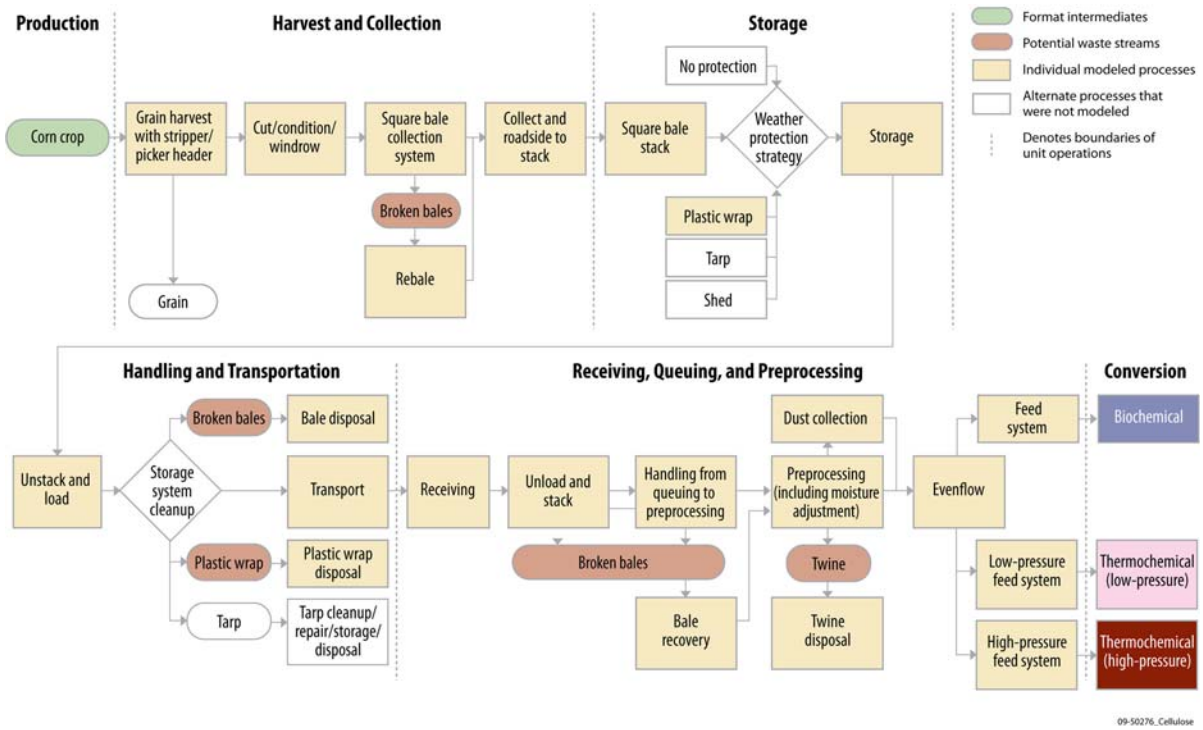

Fig. 1 Conventional Bale corn stover (Conventional Bale Stover) feedstock logistics supply system process flow schematic showing individual processes nested within unit operations

- Production: all processes to the point of harvest. Production addresses important factors, such as selection of feedstock type, land-use issues, agronomic practices, and policy issues, that drive biomass yields and directly affect harvest and collection operations.
- Harvest and Collection: all processes associated with getting the biomass from the production site to the storage or queuing location. In addition to obvious processes, such as cutting (combining, swathing) and hauling, this often includes some form of densification, such as baling, to facilitate handling and storage.
- Storage: all processes essential for accommodating seasonal harvest times, variable yields, and delivery schedules. The objective of a storage system is to provide the lowest-cost method (including cost incurred from losses) of holding the biomass material in a stable form until it is called for by the biorefinery.
- Handling and Transportation: all processes involved in moving the biomass from one point to another throughout the supply system. Handling is defined as moving biomass short distances, such as within a facility or when loading or unloading transport equipment, and occurs within all unit operations. Handling equipment, such as loaders, conveyers, bins/hoppers, pneumatics, and even slurry pumps, can be used to move biomass. Transportation is defined as moving the biomass between two or more geographically distant locations. Transportation options are generally fixed and well defined for specific locations throughout the country and can include truck, rail, or barge. Handling and transporting methods are highly dependent on feedstock format and bulk density, which makes them tightly coupled to each other and all other operations in the feedstock supply system.
- Receiving, Queuing, and Preprocessing: all processes for receiving and holding the biomass, and then physically transforming it into the format and specifications required by the biorefinery. Preprocessing can be as simple as reducing the size of the biomass for increased bulk density or improved conversion efficiency, or it can be as

complex as improving feedstock quality through fractionation, tissue separation, drying, or blending to meet chemical specifications required by the conversion facility.

A prevalent existing system for handling corn stover is to cut and bale the residue after the grain harvesting process is complete and then manage the baled residue using similar processes as other baled residue products (such as cereal straws). This paper terms this method a "Conventional Bale" feedstock supply system (Fig. 1). This supply system represents a proven approach for collecting and delivering corn stover to a biorefinery with currently available technologies. This paper (1) discusses the logistics of a corn stover supply system using existing technology and agronomic systems, (2) analyzes the corn stover supply system according to stover material property impact on logistics, and (3) discusses opportunities within each unit operation to optimize and engineer Conventional Bale Stover supply systems that can be used to supply biorefineries in the near term.

Corn stover feedstock supply system model parameters and unit operation costs

The Conventional Bale corn stover supply system (Conventional Bale Stover) configuration modeled in this analysis is based on large square bale forage harvesting and handling technologies. All preprocessing operations occur at the biorefinery. This system is designed to supply a biorefining facility with 800,000 DM tons of biomass annually (Table 1). The design can deliver ~2,300 DM ton/day, and is considered appropriate for both biochemical (Aden et al. 2002) and select thermochemical (Phillips et al. 2007) conversion facility designs that depend on a year-round biomass delivery schedule.

The Conventional Bale Stover design is based on currently available technologies and existing infrastructure, regardless of the geographical region in which a biorefinery operates. This design formats the stover in large, square (4 × 4 × 8-ft or 3 × 4 × 8-ft) bales. Round bales and other biomass collection formats may follow similar design concepts, but the calculated efficiencies and costs would vary from the square bale design modeled here.

Table 1 Conventional Bale Stover supply system design size annual capacity assumptions

Plant operation size (delivered ton[a])	800,000 DM ton/year
Feedstock harvested annually[b]	860,000 DM ton
Cultivated acres	2,107,000
Acres available for contract	1,054,000
Participating acres	50%
Corn acres harvested annually	527,000
Feedstock draw radius[c]	45.3 miles

[a] US short ton = 2,000 lb

[b] Extra tonnage harvested to account for supply system losses of 7.5%

[c] Assumes an equal distance distribution of acres throughout the draw radius

Grower payment

This design analysis was conducted under the simplified assumptions that sufficient biomass quantities can be accessed within a cost-effective transportation radius of the biorefinery delivery point, and that grower participation in lignocellulosic biomass production (including grower's decisions on land-use allocations) is equally distributed throughout that radius. The design also assumes that the corn stover removal limit has been determined to meet the producer's agronomic sustainability needs and there is surplus stover or stover fractions available for removal.

While biomass resource mix can significantly impact supply system designs, this analysis assumed a 100% corn stover supply system. For purposes of calculating a final cost for feedstock delivered to the conversion process, the corn stover value was accounted for by just adding a minimum grower payment to the final logistics cost. In the absence of any formal market prices for corn stover residue, the grower payment is estimated as a function of the nutrient and organic matter value of the removed residues, plus a grower profit from the sale of the residues.

The nutrient value is determined as a product of the price of fertilizer and the amount of nutrients in the removed stover. This value is not entirely straightforward given the regional variation in fertilizer prices by nutrient and fertilizer product, and the variation in nutrient content of the residue itself. There are many nitrogen (N) sources with prices varying considerably among them. Anhydrous ammonia is the least expensive and is generally applied to corn. Ammonium nitrate tends to be the most expensive, with nitrogen solutions and urea falling in between. The source of most phosphorus is diammonium phosphate (DAP) and monoammonium phosphate (MAP). These sources are less expensive than the less-used triple superphosphate. For potassium, muriate of potash is used almost exclusively.

Fertilizer prices vary considerably from year to year and by region. However, in 2008, prices increased dramatically because of a combination of factors, including rising energy costs and the energy-intensive nature of production, higher raw materials (i.e., natural gas) and transportation costs, as well as a sharp increase in worldwide demand. To account somewhat for year-to-year variability, average regional prices from 2006 to 2008 were used to quantify the nutrient value of the removed corn stover residue. In addition, the nitrogen embodied in phosphorous (18% N in DAP and 11% N in MAP) was valued at the 2006–2008 average regional price of anhydrous ammonia, plus a $0.05/lb application cost.

The literature indicates that the nutrient content of corn stover is somewhat variable. Data from Nielsen (1995), Lang (2002), Gallagher et al. (2003), Schechinger and Hettenhaus (2004), and Fixen (2007) were used to estimate an average nutrient composition of removed corn stover. For nitrogen, composition ranged from 13.3 to 19.0 lb/DM ton, with a mean of 14.8 lb/DM ton. The phosphorous (as P_2O_5) composition ranged from 3.2 to 7.0 lb/DM ton, with a mean value of 5.1 lb/DM ton. The range for potassium (as K_2O) was 19.7 to 35 lb/DM ton, with a mean value of 27.2 lb/DM ton.

Most corn produced in the US is grown in rotation with soybeans. As corn stover decomposes in the field, nutrients become available. P and K are not generally lost and are used by all crops. There is a question as to whether N becomes available during the soybean year of a corn-soybean rotation. Lang (2002) and Schechinger and Hettenhaus (2004) do not value the N in the corn stover in a corn-soybean rotation under the assumption that the soybeans do not need the N. However, Brechbill and Tyner (2008) point out that the N application to soybeans following corn is generally reduced due to the N carried over from the corn crop. As such, if the N carryover is reduced because of residue removal, greater N application will need to be applied to the soybean crop. Therefore, Brechbill and Tyner (2008) claim that the removed N, associated with stover removal, must always be accounted for regardless of the crop rotation. A question is whether the N that is released during the soybean year (and is not used by the soybeans) remains in the soil to be used by the corn crop in the following rotation. The approach taken in this analysis was to assume that the nutrients from corn stover become available in a linear fashion over a 10-year period and are discounted using a 6% rate. If the N released during soybean years is fully valued (in the year of the soybean crop) and discounted, the value of the N is 78% of its undiscounted value.

To account for the unknown value of the residue for organic matter, $1/DM ton is added to the nutrient value. Brechbill and Tyner (2008) add 15% of the value of the nutrients, cost of collecting corn stover, DM loss, and storage premium. In their second corn stover example, this amounts to $4.32/DM ton. This 15% premium is applied to the nutrient in addition to organic matter value. Depending on the region, this allows a profit of about $2.00–$2.50/DM ton.

Thus, the US average grower payment, which does not include harvesting, moving material to storage, or any other logistic operations, is $15.90/DM ton of removed corn stover. This is a weighted average based on the number of corn acres within each region. Minimum grower payments are lowest in the Northern and Southern Plains and highest in the Pacific and Mountain states (Table 2). For the Corn Belt region, the minimum grower payment is the same as the national average when rounded. Use of 2008 fertilizer prices would significantly increase the value of the grower payment based on nutrient and organic matter value, plus grower profit to $22.30/DM ton. Using 2006 and 2007 fertilizer prices, the grower payment would be $12.30 and $12.90/DM ton, respectively.

Harvest and collection design

Harvest and collection encompasses all processes associated with moving biomass from the production location to the storage or queuing location (Fig. 1). These processes generally consist of cutting, gathering, densifying, and transporting from the field to field-side storage. Depending on a number of variables, the specific processes, equipment, and associated costs

Table 2 Grower payments estimated regional corn stover minimum selling price

USDA production region	Average regional fertilizer prices from 2006–2008 ($/lb)			Grower payment ($/DM ton)
	Anhydrous ammonia ($/lb N)	DAP/MAP ($/lb P_2O_5)	Muriate of potash ($/lb K_2O)	
Northeast	0.37	0.48	0.30	16.10
Appalachia & Southeast	0.36–0.37	0.46–0.48	0.30–0.32	16.30
Delta	0.33–0.36	0.46–0.47	0.30–0.32	16.10
Corn Belt & Lake States	0.38	0.41	0.30	15.90
Northern plains	0.35	0.44	0.29	15.40
Southern plains	0.33	0.47	0.30	15.50
Mountain	0.42–0.46	0.49–0.56	0.30–0.33	19.30
Pacific	0.42–0.46	0.49–0.56	0.30–0.33	17.60
US average	0.37	0.45	0.30	15.90 ± 0.65[a]

Notes: Corn Stover nutrient composition was 14.8 lb/DM ton for N, 5.1 lb/DM ton for P_2O_5, and 27.2 lb/DM ton for K_2O. The range in fertilizer prices in some regions reflects overlapping of USDA fertilizer and production regions

[a] Weighted average based on the acres of corn stover in each of the respective US regions

may vary significantly from one feedstock to another. Typical operations used to harvest and collect corn stover (or crop residue) within the Conventional Bale Stover system include the two-step process of harvesting the grain, and then harvesting and collecting the residue. The feedstock intermediate formats (the transitioning physical state of the biomass as it moves through the supply system processes) play crucial roles in determining both the type and the size of the equipment used, and the timeliness of the operations necessary to control the feedstock as it moves through the supply system (Table 3).

Following grain harvest, the standing corn stover is cut, conditioned, and windrowed for baling (Fig. 2b shows windrow ahead of tractor).

Corn stover crop residue will require some level of in-field moisture management. In the Conventional Bale Stover design, the stover is cut and conditioned using a flail shredder, and through subsequent field drying, the ~50% (w.b.) moisture of the standing feedstock is reduced to ~12% (w.b.) in the windrow (Table 3). This design is not suitable for regions where stover cannot be field-dried sufficiently to be baled safely, and other moisture management methods would need to be considered.

Corn grain is usually harvested between 15 and 30% grain moisture (w.b.; Shinners et al. 2007; Hoskinson et al. 2007). Moisture of corn stover at the time of harvest is reported to be roughly twice that of the grain and ranges from 30 to 60% (Shinners et al. 2007). Pordesimo et al. (2004) reported stover moistures ranging from 40 to 66%, while Hoskinson et al. (2007) reported stover moistures as low as 25%. Even at the lowest reported stover moisture, field drying of the biomass prior to baling is required. As an alternative to stover in-field drying, Hoskinson et al. (2007) suggest a fractional harvest of cobs, husks, and upper stalk, which could be within the moisture limit for dry storage at the time of grain harvest. These and other advanced harvesting concepts are discussed in Hess et al. 2009.

When field drying is used, as in this design, the selection of stover harvest operations must occur with consideration to ambient conditions. During good drying conditions, cutting and windrowing can be performed simultaneously with a single machine, thus eliminating the raking operation (the assumed scenario in Table 3). However, if less-than-ideal drying conditions exist, the feedstock might need to be spread thinly in the field with a mowing operation and then raked into a windrow prior to baling. In either case, there are significant risks associated with field drying because it increases the chances of precipitation exposure and weather-related harvesting delays. In the case of late fall harvests, these delays may altogether prevent drying of the feedstock. If field drying is prevented, the stover crop cannot be collected and handled using this Conventional Bale Stover design, and alternative supply system designs that can handle unstable high-moisture biomass materials will need to be considered (Hess et al. 2009).

Table 3 Equipment and format intermediate attributes modeled for the Conventional Bale Stover harvesting and collection operation and estimated costs

Logistics processes	Production	Grain harvest	Condition & windrow	Baling	Collect & roadside to stack	Dry matter loss	Total harvest & collection costs
Equipment	N/A	Combine with 8-row corn header	180 hp tractor and 15-ft flail shredder with windrowing	275 hp tractor and large square baler	Self-propelled stacker		
Format intermediates	Standing crop	Stubble—standing stalk; cob and husk on ground	Windrow	Randomly distributed 4 × 4 × 8-ft bales[a]	Collected at field side 4 × 4 × 8-ft bales[a]		
Biomass description	Whole crop (grain and residue)	Stalk, cob, and husk (collectively stover)					
Yield (DM ton/acre)[b]	8.52 (180 bu/acre corn)	4.26	3.0	1.6 (2.8 bale/acre)	1.6		
Bulk DM density	N/A		~0.8–0.9 lb/ft^3 (1.04 ton/1,000 windrow-ft[c])	9 lb/ft^3 (1,150 lb/bale)[d]			
Moisture (w.b.)[e]	50%		12%				
Modeled cost totals[f] ($/DM ton)	No cost[g]		4.16 ± 0.65	10.91 ± 1.11	1.89 ± 0.32	4.65 ± 1.91	21.61 ± 2.69
Modeled cost totals[f] ($/acre)	No cost[g]		12.27 ± 1.53	15.86 ± 3.62	2.75 ± 0.75	6.26 ± 1.38	37.14 ± 4.25

[a] The Conventional Bale Stover supply system is based on the 4 × 4 × 8-ft bale, though other large square bale formats are available, including 3 × 4 × 8-ft low- and high-density formats

[b] Process output yield calculations based on equipment dry matter loss: grain harvest 1:1 residue-to-grain ratio, or harvest index of .5; condition and windrow collection efficiency of 71%; baling collection efficiency of 54%; and collect and roadside collection efficiency of 100%

[c] Windrow size is based on a 15-ft swath × yield/acre. (Windrow bulk density is estimated at 10% of bale bulk density; however, biomass material size and weathering can greatly influence windrow volume.)

[d] Shinners et al. 2007

[e] Hoskinson et al. 2007

[f] Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario

[g] Harvest costs associated with grain are not included in the cost of the feedstock since they are born by the grain industry

Fig. 2 Corn stover **a** standing in the field (*background*), and stover stubble after grain harvest (*foreground*); **b** windrowed with a mower/conditioner (*front* of tractor) and baled in a 4 × 4 × 8-ft format; and **c** in randomly distributed 4 × 4 × 8-ft bales dropped from the baler as they are made, which is the starting configuration for the modeled Conventional Bale Stover design

Once the feedstock in the windrow reaches ~12% moisture (w.b.), a baler picks up the windrow and produces large 4 × 4 × 8-ft square bales that are dropped in the field as they are made (Fig. 2c). Bale accumulators can be attached to the back of the baler (such as the one shown in Fig. 2b), allowing the bales to be gathered into rows across the field. However, for this design, a bale accumulator is not used, resulting in a random distribution of bales throughout the field.

The randomly distributed bales are then collected and transported to a bale collection point at the side of the field ("field side"; Fig. 3). The bale collection point is generally located next to a road that borders the field or is nearby (e.g., less than 5 miles away). This collection operation is often referred to as "roadsiding." Once the bales are roadsided to the bale collection location, the harvest and collection unit operation is complete.

The estimated cost for the harvesting and collection unit operation is $21.61 ± 2.69 per ton or $37.14 ± 4.25 per acre based on about a 1.6 ton per acre net stover yield (Table 3). These cost estimates also account for the cumulative cost of material losses with each process (Table 3, DM Loss column).

Storage design

Storage encompasses all processes associated with stacking, protecting the biomass from weather or other environmental conditions, and storing the biomass in a stable condition until called for by the biorefinery (Fig. 1). In the Conventional Bale Stover design, storage does not include biomass material stabilization (i.e., drying or ensiling) because stabilization of the biomass material occurs with the field-drying process during harvest, and the bale moisture has already been reduced to ~12% (Table 4). The Conventional Bale Stover storage design employs technologies and methods to protect the bales from both mechanical and biological losses, but the model assumes a 5% physical loss, or shrink, during storage (Table 4).

The storage configuration for the Conventional Bale Stover design is on-farm stacks of bales located at or near the field side (Fig. 4). While there are several options that can be used to protect stacks of bales from weather damage, this design uses a plastic wrap storage system because it meets the weather protection requirements and provides a workable

Fig. 3 Stinger Stacker 5500 picking up (**a**) and stacking bales (**b**) at bale collection point

biomass storage system for all baled biomass in any environment.

The selection of the best storage strategy depends upon local conditions. This Conventional Bale Stover design uses a 1-bale-wide × 2-bale-high stack configuration (Fig. 4). While this configuration is necessary for the chosen plastic-wrap process, it is fairly inefficient in terms of land area use. If land area use is inexpensive and available, as this design assumes, this configuration is a cost-effective solution. If land area use is expensive (e.g., improved storage site, summer storage that idles cropping acres, etc.), the two-bale-high stack configuration may not be feasible due to inefficiency. A more efficient land-area-use stack configuration is 4 bales high in either single or multiple adjacent rows. In an enclosed structure, the stack might be 6–8 bales high to achieve the highest possible land area use. Determining the best storage configuration is a trade-off between storage system costs and the potential biomass DM loss (Table 5).

Table 4 Equipment and format intermediate attributes modeled for the conventional bale stover storage operation and estimated costs

Logistics processes	Stack bales	Protect bales	Store bales	Dry matter loss costs	Total storage costs
Equipment	Self-propelled loader	Bale wrapper	Insurance, land rent, stack maintenance		
Format intermediates	Rows of plastic wrapped 4 × 4 × 8-ft bales, stacked 1-bale wide and 2-bales high at field side				
Biomass description	Stalk, cob, and husk (collectively stover)				
Stack size[a]	200 DM ton/stack (348 bales)		190 DM ton/stack (348 bales)		
Bulk DM density output[b]	9 lb/ft^3 stack (0.13 acre/stack)				
Output moisture (w.b.)	12%				
Modeled cost totals[c] ($/DM ton)	0.91 ± 0.13	5.66 ± 0.34	0.10 ± 0.01	1.44 ± 0.44	8.11 ± 0.66

[a] Assume 5% shrinkage of yielding DM tons during storage (i.e., loss of original biomass DM); actual wet tons may be equal to or greater than starting tonnage

[b] Assumes wrapping results in tight stack with the same bulk density as the bales

[c] Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario

Fig. 4 Plastic-wrapped row of field-side bale stacks (**a**) that were wrapped with a Stinger 4000 Cube-line wrapper (**b**)

Using storage structures or wrapping bales costs more but has the potential to save significantly on DM loss.

The Conventional Bale Stover storage system objective is to maintain the original biomass properties throughout the duration of storage, so that when the biomass is retrieved from storage, it is as close as possible to its original condition. The estimated cost for the storage unit operation is \$8.11 ± 0.66 per ton (Table 4). The storage cost estimate accounts for the material loss in storage (Table 4, DM Loss column). Storage losses are often referred to as "shrinkage." Storage shrinkage and quality degradation factors can include physical loss (e.g., stack wind erosion or handling losses), bulk settling, moisture partitioning, dust accumulation, and some degree of biological impacts resulting from combinations of filamentous fungi, bacteria, insects, and rodents. Additionally, the moisture content may increase due to precipitation or humidity, or, in arid environments, the moisture content may decrease due to prolonged evaporation. Moisture increases during storage generally accelerate detrimental microbial activity; thus, preventing moisture increases will slow such microbial activity.

The amount of moisture that can be allowed into the biomass before substantial damage occurs is case-specific and subject to debate; however, the underlying principles are relatively consistent. Microbes react more to an index termed "water activity" (aw) than to the bulk percentage of moisture in the biomass. This water activity represents the equilibrium amount of water available to microorganisms and enzymes, and it corresponds to the equilibrium relative humidity divided by 100 (Troller and Christian 1978). An "aw" measurement of 1.0 represents pure water that is unbound, while an "aw" value of zero would indicate completely dry material with no water available. Molds and filamentous fungi will grow at a water activity of 0.7–0.9, and only a select number of organisms grow below the 0.7 level. As such, a dry storage system should be designed to keep the water activity of the biomass at 0.7 or below to

Table 5 Modeled comparison of typical storage improvements and structure costs compared to dry matter loss and its impact on feedstock costs

	% Dry matter		Ownership cost of structure or improvements (\$/DM ton)[c]	Cost of dry matter loss (\$/DM ton), at feedstock cost of \$22.19/DM ton[d]	
	Dry climate loss, range	Wet climate loss, range[b]		Dry climate	Wet climate
Stack on ground	1–9	7–39	0.07 (taxes)	1.20	4.30
Stack on improved ground surface	4–18[a]	7–36	0.40–1.60[e]	1.50	3.30
Covered stack on ground	3–13[a]	6–25	1.50	1.50	3.30
Covered stack on improved surface	1–5[a]	2–10	1.80–3.02	0.50	1.10
Bale wrap on ground	1–4[a]	1–8	6.20	0.60	1.20
Pole barn	1–4[a]	2–7	12.30	0.50	1.00
Totally enclosed shed/building	1–4[a]	2–8	14.10	0.40	0.90

[a] Due to the lack of data on dry matter loss in dry climates, dry matter loss values in dry climates are calculated based on a relationship illustrative by Holmes (2004) as 0.5 × wet climate values (Hess et al. 2009)

[b] Multiple data sources (Hess et al. 2009)

[c] Ownership costs are based on a structure to accommodate 100 DM tons, property tax of \$300 per acre (Bruynis and Hudson 1998; Edwards and Hofstrand 2005), improvement tax rate of 2%, maintenance cost of 2% per year. Details of construction costs are available in the works cited

[d] Cost of dry matter loss in the delivery chain from harvest up to the point of discharge from storage is: (delivered cost)/(1-\$dry matter loss)—(delivered cost), where "delivered cost" is the cost of feedstock delivered to storage

[e] Range of site preparations is between grading with packed gravel at \$0.60/ft^2 and concrete hardstand at \$3.00/ft^2. (Low and high values from a telephone survey of eight paving contractors in five midwestern states). Only gravel improvement is used in this comparison (Dhuyvetter et al. 2005; Shinners et al. 2007)

prevent the degradation of biomass by most filamentous fungi and bacteria, which will in turn reduce DM losses in the feedstock.

Like forage bale storage systems, moisture content of bales going into the storage stack is of particular concern due to the spontaneous combustion risk of high-moisture bales (Gray et al. 1984; Clark 1993). The modeled Conventional Bale design only accepts bales into storage at or below 12% moisture, which is a safe moisture range for bale stack storage of biomass. This design also employs a plastic-wrap storage system, which is one of the most aggressive bale protection systems available for field-side storage (Fig. 4b). Even with a bale wrap storage system, there will still be some loss (shrinkage) that occurs during storage, which, for this model, is set at 5% (Table 4, stack size change).

Handling and transportation design

The handling and transportation operation comprises all activities required to transfer baled material from long-term, field-side storage to shorter-term, bale-yard storage (or queuing) at the biorefinery (Fig. 1). As modeled here, these processes use self-propelled loaders to handle the bales onto a flatbed semi-tractor trailer for transport at a rate of about 80 bales/h (Fig. 5a).

This design uses a 53-ft flatbed semi trailer that hauls 26 bales within the 53-ft trailer length constraints or 28 bales with a trailer extension (Fig. 5b). The model assumptions are constrained to 26 bales per load, and after accounting for storage shrink, DM hauled out of storage is estimated at 28,500 lb per load (Table 6). The actual truck net weight would be about 32,000 lb due to the bale moisture of 12%.

The modeled Conventional Bale Stover design calculates a mean transportation distance to the biorefinery based on a supply radius of 45.3 miles. Using the combined variables of feedstock yield, total cultivated acres, acres of desired feedstock in production, and acres of feedstock in contract with the biorefinery, the mean transportation distance for this design is calculated to be 31.5 miles. Taking into

Fig. 5 Loading two 4 × 4 × 8-ft bales at a time onto a flat-bed semi-tractor trailer (**a**) and loaded bales strapped and ready for transport to the biorefinery (**b**)

Table 6 Equipment and format intermediate attributes modeled for the conventional bale stover handling and transportation operation and estimated costs

Logistics processes	Load truck from stack	Transport load	Total handling & transportation costs
Equipment	Self-propelled loader	3-axle day cab tractor with 53-ft flat bed trailer	
Format intermediates	4 × 4 × 8-ft bales		
Biomass description	Stalk, cob, and husk (collectively stover)		
Load size (DM lb/load)	28,500 (26 bales)		
Bulk DM density	8.55 lb/ft^3		
Moisture (w.b.)	12%		
Modeled cost totals[a] ($/DM ton)	0.84 ± 0.09	11.09 ± 1.22	11.93 ± 1.25

[a] Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario

account a winding factor of 1.2 for the haul distance to the biorefinery, the final transportation distance for the Conventional Bale Stover design is 37.8 miles for this modeled scenario.

The estimated cost for the handling and transportation unit operation is $11.93 ± 1.25 per ton, and the modeled design assumes that no DM losses are incurred in this unit operation (Table 6).

Estimating the cost of the handling and transportation unit operation often focuses on just the transportation distance in terms of dollar per mile. Though this method of estimating transportation costs may be reasonable, it erroneously suggests that transportation distance is the most important parameter impacting the total handling and transportation cost. Transportation distance represents only the variable cost component of the total cost, and in some cases, the fixed costs associated with loading and unloading the transport container (semi-tractor trailer, rail car, etc.) can be more significant. The relative contribution of both the fixed and variable cost components is illustrated in a typical handling and transportation operation where 26 large square bales (4 × 4 × 8-ft) of corn stover are transported on a standard 8-ft wide × 53-ft-long semi-tractor trailer with a payload of 32,000 lb. In this example, bales are loaded and unloaded two at a time at a rate of 80 bales/h using a self-propelled loader. As shown in Fig. 6, the fixed costs, totaling about $58 per load, exceed mileage costs up to a hauling distance of about 18 miles. Note that the dollar per DM ton-mile cost rises sharply within this 18-mile haul distance due to the high fixed cost. The total cost per DM ton increases linearly with transportation distance where the fixed costs alone account for $4.20 per DM ton.

The fixed and variable costs of transportation are subject to the same prevailing constraints affecting all supply system operations: capacity and efficiency. Within the diversity of the Conventional Bale Stover system, these constraints are impacted by a number of feedstock, equipment, and infrastructure attributes, including feedstock format, feedstock bulk density, moisture content, transportation distance, load capacity, weight limits, and DM losses.

The square bale format is the most significant variable impacting handling and transportation processes in the Conventional Bale Stover design. Handling and transportation costs are directly impacted by the relatively low bulk density of baled feedstock, typically around 6–10 lb/ft^3 (Table 6). This relatively low bulk density format makes it difficult to load enough bales on a truck to reach the gross vehicle weight (GVW) limit required for optimizing delivery systems. The bulk density required to maximize various truck configurations to accommodate a range of load limits is shown in Table 7, and the load configurations are shown in Fig. 7. Again, as a reference, large 4 × 4 × 8-ft square bales of corn stover at 12% moisture typically weigh ~1,300 lb and have a DM bulk density of 9 lb/ft^3, or about 10 lb/ft^3 wet density. Thus, baled corn stover almost maximizes the load capacity of the third truck configuration (Table 7), which is allowed in some western and midwestern states.

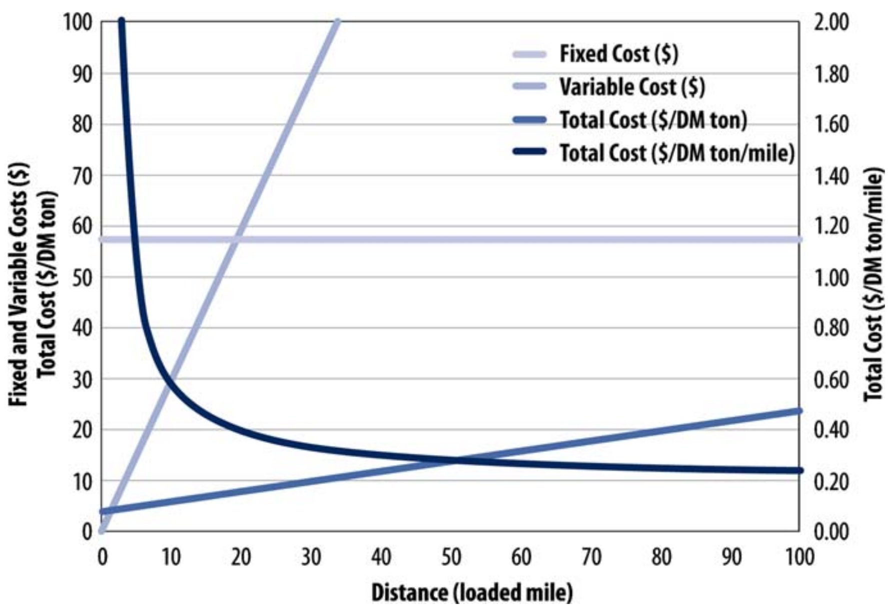

Fig. 6 Transportation costs for hauling large square bales of corn stover with a semi-tractor trailer

Table 7 Bulk density required to maximize various load capacity configurations to accommodate a range of load limits

Truck configurations[a]	Load limits		Payload			Maximum load bulk density (lb/ft^3)	
	Length (ft)	GVW (lb)	Max (lb)	Bale count			
				3×4×8-ft	4×4×8-ft	3×4×8-ft	4×4×8-ft
1. 48-ft flatbed trailer	48[b]	80,000[b]	51,100	36	24	14. 8	16.6
2. 53-ft flatbed trailer	53[c]	80,000[b]	50,800	39	26	13.6	15.3
3. 24-ft flatbed tractor pulling two 30-ft flatbed trailers	105[d]	105,500[d]	59,500	66	44	9.4	10.6

[a] Impacts on transportation costs for these configurations are discussed in greater detail in Sect. 2.3.2.2

[b] Federal limits

[c] Common state maximum on national network (NN) highways

[d] Allowable common limits in CO, ID, KS, ND, NE, OK, and SD for two trailing units on non-NN highways

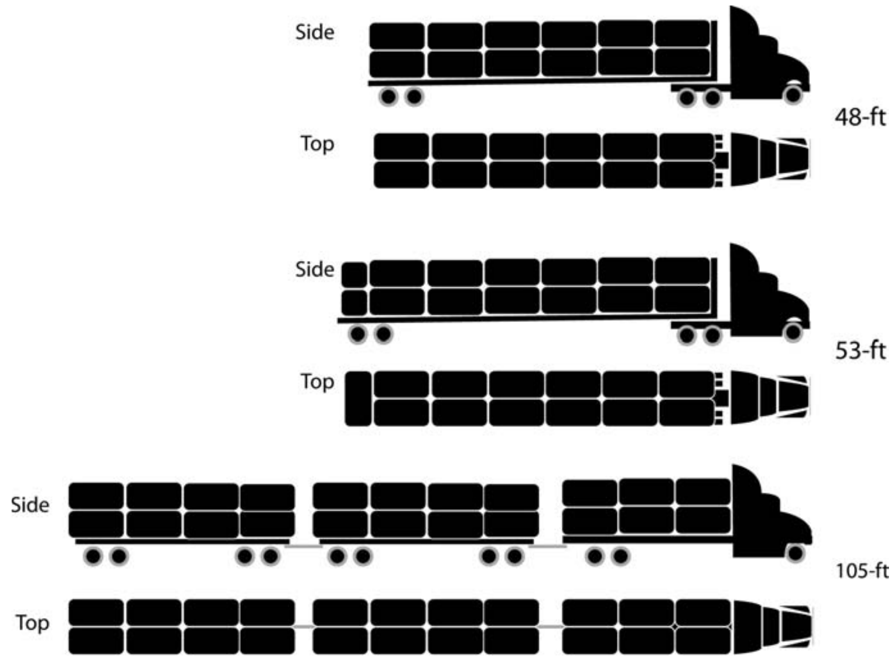

Fig. 7 Truck configurations for a 48-ft trailer, a 53-ft trailer, and a 24-ft flatbed tractor with two 30-ft trailers

Receiving, queuing, and preprocessing design assumptions

Biorefinery receiving and preprocessing encompasses processes associated with weighing and unloading incoming trucks, moving baled feedstock into short-term storage (queuing), moving bales from queuing into the preprocessing system for grinding, and feeding the ground feedstock into the conversion process (Fig. 1). The Conventional Bale Stover preprocessing design requirement is to simply shred the bale and size-reduce the biomass sufficiently to move it through the feed system and into the conversion reactors. In reality, such a simplified preprocessing system may not be adequate for some conversion processes, and additional or alternate preprocessing systems may be required for the conversion system to function properly, but such systems are not modeled herein. The Conventional Bale Stover design only receives biomass 14 h each day, while the biorefinery operates 24 h each day. Therefore, approximately 190 truck loads of 26 bales each will be received daily within a 14 h operating window, and over the full 24 h period, 4,000–5,000 bales will be removed from the bale yard queue and preprocessed for conversion (Table 8). As such, a feedstock inventory will be maintained for immediate access while feedstock delivery is suspended during off-shift hours or during weather delays. In this design, the queuing bale yard will hold a 72 h feedstock inventory; however, depending on the receiving schedule and the probability of weather events that could halt delivery operations, a larger storage queue may be required. The queuing bale yard is intended to be a first-in/first-out queue; thus, feedstock inventory is rotated at a regular interval.

The size of bale queue yard stacks is limited to 100 tons (as received), and each stack is separated by a 20-ft clearance, as required by the International Fire Code (ICC 2003; Fig. 8). The large 4 × 4 × 8-ft square bales are stacked four high and five wide, and depending on the bale density, from 6 to 10 bales long for a 100-ton stack.

Following the same schedule as the conversion facility, stacked bales are moved from the bale queue yard to the grinder, and the bales are preprocessed into a bulk format for insertion into the feed systems of the conversion process (Fig. 9). The bulk density of the stover at this point is approximately 7.4 lb/ft^3, with similar moisture content as the pre-ground, baled material (12% w.b.; Table 9).

The physical characteristics of biomass feedstocks are related to the ultra structure of the different plant components, such that even though the same grinding mechanism is used, each anatomical plant part and the component plant tissues contribute to different end-product properties (Table 9). Grinding corn stover in a tub or horizontal grinding system with hammers or fixed cutters results in a significant amount of strong fibrous material that does not easily reduce in size and flow through the separation screen. This material becomes interlocked, forming a low-bulk-density mat that can sit on top of the grinding chamber after the rest of the stover has been discharged from the system. This mat of fibrous stover tissues can significantly reduce the overall capacity of the grinder and even plug the grinder separation screen and discharge area. The matting problem can be overcome by increasing milling shear forces (e.g., knives, shear plates, etc.) to more efficiently size-reduce this highly fibrous material. Of course, the non-fibrous stover tissues rapidly

Table 8 Equipment and format intermediate attributes modeled for the Conventional Bale Stover receiving, queuing, and preprocessing operation and estimated costs

Logistics processes	Receiving & queuing			Preprocessing				Total receiving & preprocessing costs
Equipment	Truck scales and asphalt storage	Self-propelled loader	Self-propelled loader	Grinder in-feed system	Horizontal grinder	Dust collection system	Surge bin and conveying equipment	
Format intermediates	4 × 4 × 8-ft bales			Bulk (1½-in. minus)				
Biomass description	Stalk, cob, and husk (collectively stover)							
Capacity (DM ton/day)	2,300 (4,640 bales)[a]			2,300				
Bulk DM density	8.55 lb/ft^3			7.4 lb/ft^3				
Moisture (w.b.)	12%			12%				
Modeled cost totals[b] ($/DM ton)	0.37 ± 0.01	0.84 ± 0.09	0.76 ± 0.04	1.54 ± 0.09	7.71 ± 0.96	1.76 ± 0.19	0.76 ± 0.05	13.74 ± 1.31

[a] Total tonnage and bale number for the bale yard queue is the daily volume processed (24 h period at 2,600 DM ton) multiplied by 3 days (72 h queuing period), which equals a 6,900 DM ton queue yard capacity, or about 11,000 bales

[b] Cost totals represent the mean and standard deviations of 10,000 model iterations for the simulated scenario

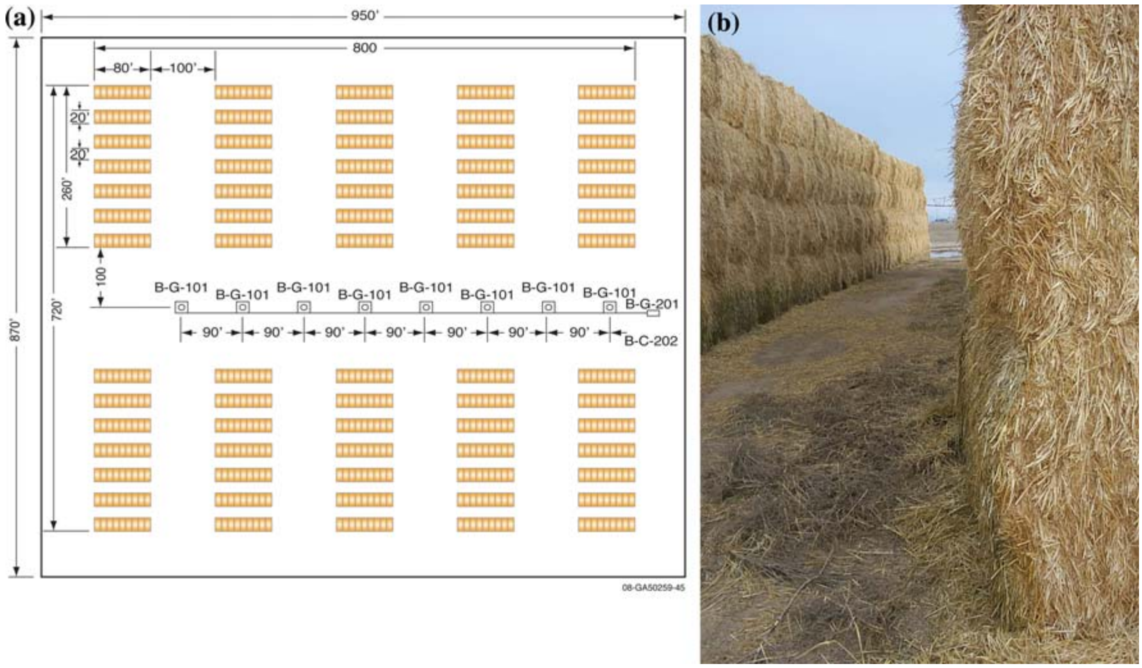

Fig. 8 Conventional Bale Stover receiving and queuing: **a** bale queuing yard layout and **b** lane separating two stacks of 4 × 4 × 8-ft bales in a bale yard

Fig. 9 Corn stover feedstock preprocessed through a nominal 1–1/2 in. minus grinder screen

Table 9 Material characterization after the Conventional Bale Stover preprocessing operation

Feedstock (1½-in. minus)	Corn stover
Mean particle diameter	4.0 mm
Particle-size distribution (wt%)	29.9% > 6.35 mm
	2.03 mm < 45.9% < 6.35 mm
	24.2% < 2.03 mm
Bin density (10-ft diameter bin)	7.4 lb/ft^3
Compressibility (Δ% 0–500 lb/ft^2)	66.0 ± 0.5%
Flowability factor[a]	0.8 (non-flowing)
Springback	40.6 ± 1.4%
Angle of repose	39.6 ± 4.3°

[a] Flowability factor ranges: <1.0, non-flowing; 1.0–2.0, very cohesive; 2.0–4.0, cohesive; 4.0–10.0, easy flowing; and >10, free flowing

size-reduce with impact forces, such as hammers or blunt cutters. For many biomass resources, like corn stover, a combination of multiple size-reducing actions may be the most efficient way to reduce feedstock material to the desired format and particle size. This can be achieved with a two-stage grinding system or a system where the two actions are combined in one machine.

The physical deconstruction characteristics of corn stover ground in this Conventional Bale Stover design have a mean particle size and particle-size distribution difference of 0.20 ± 0.14 in. (Fig. 10). These feedstock particle sizes and distribution may

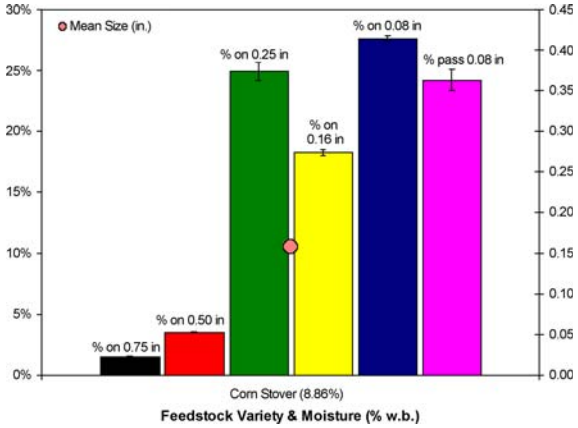

Fig. 10 Mean particle size and particle-size distribution for corn stover at the noted moisture (% w.b.). Mean particle size and distribution were determined using a forage particle separator (ASABE, ANSI/ASAE S424.1, 2007)

ultimately need to be improved based on conversion process requirements and material handling constraints. A general mean particle size target of ¼-in. minus, with no range constraint or lower size limit, was used as a baseline in this design.

Additional considerations for particle size may be dictated by bulk-flow properties required by the biomass conveyance systems into the conversion processes. For example, 1½-in. minus corn stover does not produce a flowable product (Table 9). As such, more aggressive preprocessing of corn stover may be required to achieve a desired material property characteristic, which can affect biomass feed rates and solids-loading specifications of specific conversion processes.

This modeled design scenario for corn stover incorporates equipment and systems to address regulatory issues impacting the receiving, queuing, and preprocessing operation, including dust control, fire prevention, and rodent control. The estimated cost for the receiving, queuing, and preprocessing unit operation is $13.74 ± 1.31 per ton (Table 8). Fire prevention is largely addressed by limiting the stack sizes and clearances in the bale yard according to the requirements of the International Fire Code (ICC 2003), but fire suppression systems such as hydrants are located throughout the bale yard as well. Dust collection systems within preprocessing are also designed to meet the National Fire Protection Agency's (NFPA) standard for dust explosion (NFPA 2006, 2008).

Integrated supply system analysis: performance results and discussion

An integrated sensitivity analysis of all conventional bale feedstock logistics unit operations (harvest and collection; storage; handling and transportation; and receiving, queuing and preprocessing) was conducted using an Excel-based feedstock model of the Conventional Bale Stover design just described. This sensitivity analysis did not include the grower payment. The objectives of this sensitivity analysis were threefold:

- Evaluate the effects of variability and uncertainty on the economics of supply system logistics
- Identify the probability of conventional supply technologies meeting the feedstock logistics (not grower payment) cost targets of less than 25% of the cost to produce biofuels (DOE-EERE 2009)
- Identify key barriers for improvement and optimization of supply system logistics.

A single-point sensitivity analysis was performed to determine variations of single variables with respect to the entire integrated system. This analysis was performed by uniformly varying all input variables by ±10% of the base value, and then identifying and ranking all input factors that affect the final delivered feedstock cost. Based on the ranking of input variables, resulting from the single-point sensitivity analysis, the uncertainty of each parameter was defined using a probability distribution. The probability distribution represents either the inherent variability or the uncertainty of the respective input variables, as determined by the variability in collected field data, published data (e.g., field efficiency and field speed ranges published by ASABE [ASAE D497.5 2006]), or range of operating parameters suggested by skilled operators of the equipment. The benchmark values used in the Conventional Bale Stover model were derived from the most likely value included in each distribution.

A more sophisticated Monte Carlo uncertainty analysis was then conducted by allowing the input parameters to change over their respective probability distributions simultaneously, thus representing the combined impacts of the system uncertainty and the interdependence of input parameters. This analysis was conducted using @Risk,[1] which interfaces directly

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with the Excel-based feedstock model (Palisade Corporation 2009). The simulation consisted of 10,000 iterations, for which all of the parameters were randomly varied according to their defined probability distributions, resulting in a cost distribution histogram (Fig. 11). The simulation model mode value of $53.70 per DM ton was closer to the static model summed value of $51.88 per DM ton than the simulated mean value of $55.50 per DM ton, since the defined value of the parameter distributions was set equal to the summed static value in the model. A key finding of this Monte Carlo analysis is that the Conventional Bale Stover supply system design is not able to achieve cost performance targets better than about $49.00 per DM ton, which falls short of our supply system cost performance goals (Fig. 11). Further analysis defined and ranked critically the supply system equipment and biomass material parameters that must be addressed to achieve cost improvements greater than $49.00 per DM ton.

The @Risk simulation also produced a ranking of input parameters based on the statistical relationship between each parameter and the total supply chain logistics costs to determine the impact of each parameter individually, and capture the interdependence of each respective input parameter (Fig. 12).

Comparing the rankings of individual input parameters shows that although the feedstock cost may be highly sensitive to changes in the value of a specific variable (Fig. 12a), the uncertainty or variability of that parameter may be small, and the corresponding impact on cost is small as well (Fig. 12b). Thus, the two rankings are not consistent. For example, harvest efficiency is ranked as the third highest parameter in terms of its potential influence on feedstock cost (Fig. 12a), but it ranks among the lowest (9th in Fig. 12b) in actual impact. This reveals a dual role of sensitivity analysis and requires an important distinction in the objective of the analysis. If the objective is to optimize the Conventional Bale Stover design, the rankings in Fig. 12a would be most relevant; however, if the objective of the sensitivity analysis of the Conventional Bale Stover design is to quantify the uncertainty in the design, the rankings shown in Fig. 12b are most relevant.

Finally, the cause-and-effect relationships of top cost impact parameters were examined (Fig. 12b). Baling efficiency had the largest influence on harvest and collection (Fig. 13). This influence is fairly intuitive because it directly impacts the net biomass yield. As baling efficiency increases, net biomass yield increases. The effect of increasing biomass yield decreases per ton baling costs, as well as transportation cost. The change in per ton baling costs also has a cascading effect on the DM loss value of subsequent unit operations, and thus the impact shown in storage (Fig. 13). Changes in bale bulk density demonstrated a near-equal impact on harvest and collection, storage, and handling and transportation (Fig. 13). Although the affect of bale moisture can be very significant throughout the feedstock supply system, the modeled assumption that the corn stover is able to field dry to 12% moisture limited the impact of moisture to grinding capacity in the preprocessing unit operation (Fig. 10). Higher and larger variations in moisture cannot only impact supply system costs, but also increase the risk of catastrophic failures in supply systems (Hess et al. 2009). The next four parameters—shredder field speed, baler capacity, harvest window, and baler field efficiency—are all related to machine capacity, which is an obvious parameter affecting feedstock costs. Increasing machine productivity without a proportionate increase in machinery costs improves supply system cost performance. The uncertainty of the remaining parameters was not large enough to create significant cost impacts to the supply system.

The Conventional Bale Stover feedstock supply system is a design that can be implemented by a lignocellulosic biorefinery with little to no modifications to readily available forage equipment. Based on the design presented in this paper, the final delivered feedstock cost to the infeed of the conversion process (average US grower payment plus mean logistics costs) is about $71 per DM ton (Table 10).

Conclusion

An effective Conventional Bale Stover supply system design requires the optimization of intended and minimization of unintended material property

Footnote 1 continued
name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government, any agency thereof, or any company affiliated with Idaho National Laboratory.

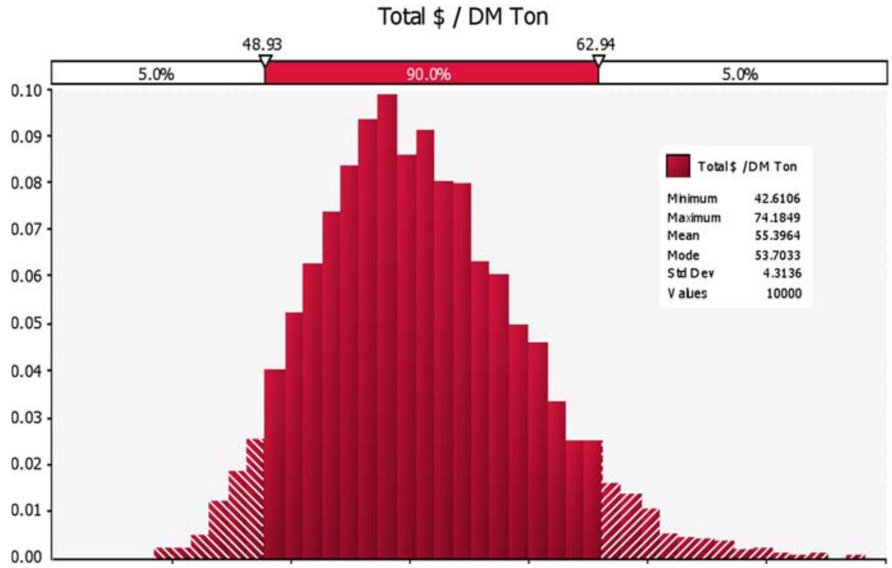

Fig. 11 Conventional Bale Stover supply system logistics cost distribution histogram from @Risk analysis (does not include grower payment)

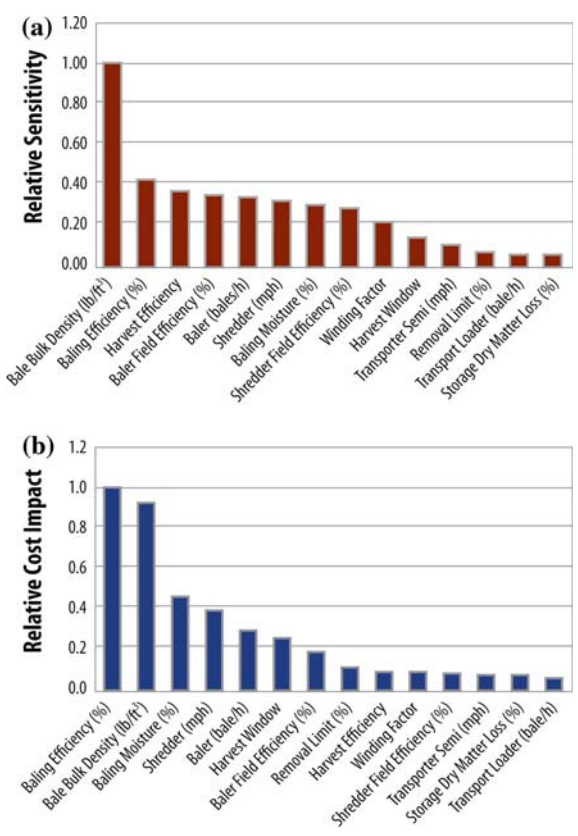

Fig. 12 **a** Relative sensitivity of individual supply system parameters and **b** relative cost impact of individual supply system parameters

changes as the corn stover passes through the individual unit operations. The parameters identified in this study as having the greatest impact on supply system costs and opportunities for optimization can be grouped into two general categories: Equipment Efficiency (shredder field speed, baler capacity, harvest window, and baling efficiency) and Material Properties (bulk density and moisture content). Each parameter influences processes throughout the supply system and provides opportunities for system improvement in each unit operation. However, simply improving equipment efficiency is not sufficient to keep feedstock logistics costs at or below 25% of the total biofuels production cost. The biomass material property challenges of low bulk density and high moisture instability must be overcome. "Baling efficiency" in this analysis, reflects the net residue yield, which, like density, is a major impediment to improving the harvest and collection operation. Harvest and collection comprises the largest cost element of the feedstock logistics system (Table 10), and of all the parameters impacting this unit operation, improvements in harvestable yield will do more to reduce harvest and collection unit operation costs than any other factor, including bulk density.

Therefore, given the stated objectives outlined in the introduction to this study, an analysis of the

Fig. 13 The affect of baling efficiency and bale bulk density on select supply chain operations

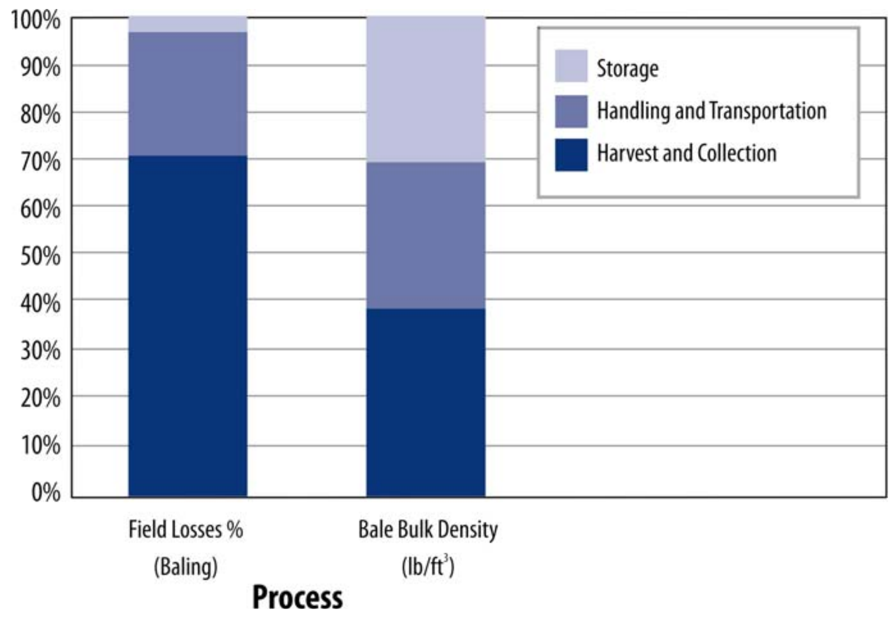

Table 10 Total delivered feedstock cost summary for the conventional bale corn stover scenarios

	Average minimum US production cost	Harvest & collection cost	Storage cost	Handling & transportation cost	Receiving & preprocessing	Total feedstock cost
Grower payment ($/DM ton)	15.90 ± 0.65					15.90 ± 0.65
Logistics cost totals ($/DM ton)[b]		21.61 ± 2.69	8.11 ± 0.66	11.94 ± 1.25	13.74 ± 1.31	55.40 ± 4.31

[a] Cost is in 2008$ and represents the weighted average of US regional costs (Table 2)

[b] Costs are in 2008$ and represent the mean and standard deviations of 10,000 model iterations for the simulated scenario (Tables 3–6)

modeled large, square-bale supply system indicates that where other agronomic factors are not limiting, corn stover can be accessed and supplied to a biorefinery using existing bale-based technologies. However, improved technologies and new supply system designs are necessary to overcome biomass bulk density and moisture material property challenges. Additionally, low crop residue yields limit the logistic efficiency of the entire supply system, but especially harvest and collection. Changes/improvements in agronomy and crop production are essential to improve crop residue yields. Harvest and collection systems for switchgrass or other high tonnage biomass crops consistently demonstrate improved costs using the same equipment (Hess et al. 2009). Finally, major opportunities to optimize conventional bale biomass feedstock supply systems for biorefining include improvements in equipment efficiency and capacity (Fig. 13) and reduction of biomass losses in harvesting and collection and storage (Tables 3, 4).

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